Reflective liquid crystal device

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Abstract

A reflective liquid crystal device comprises a polariser 1 and a mirror 2 between which are disposed several retarders 3, 4, 5. At least one of the retarders 4 is a variable liquid crystal element whose optic axis is switchable so as to switch the device between a reflective state and a non-reflective state. In the non-reflective state, the total retardance of the retarders 3, 4, 5 between the polariser 1 and the mirror 2 is equal to an odd number of quarter wavelengths for a wavelength at or adjacent the middle of the visible spectrum.

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(54) **Reflective liquid crystal device**

(57) A reflective liquid crystal device comprises a polariser 1 and a mirror 2 between which are disposed several retarders 3, 4, 5. At least one of the retarders 4 is a variable liquid crystal element whose optic axis is switchable so as to switch the device between a reflective state and a non-reflective state. In the non-reflective state, the total retardance of the retarders 3, 4, 5 between the polariser 1 and the mirror 2 is equal to an odd number of quarter wavelengths for a wavelength at or adjacent the middle of the visible spectrum.

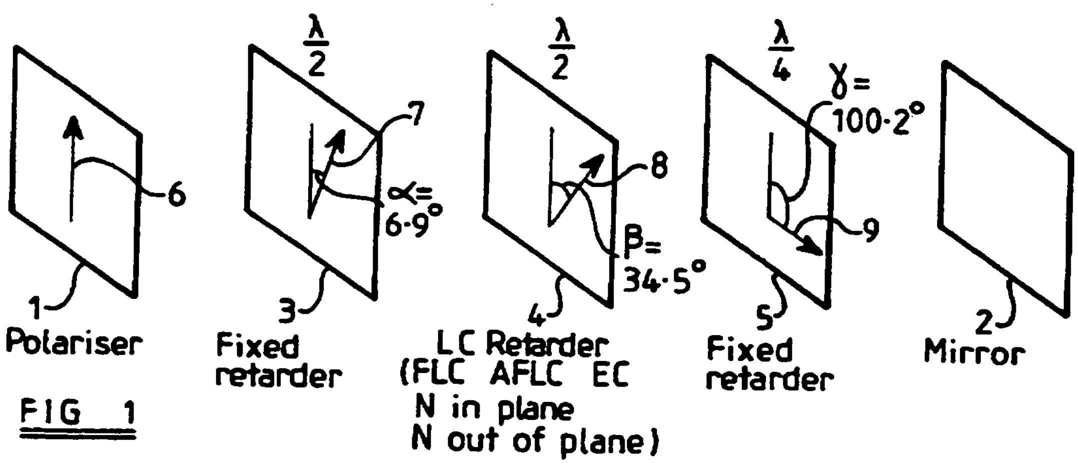


FIG 1

GB 2 318 878 A

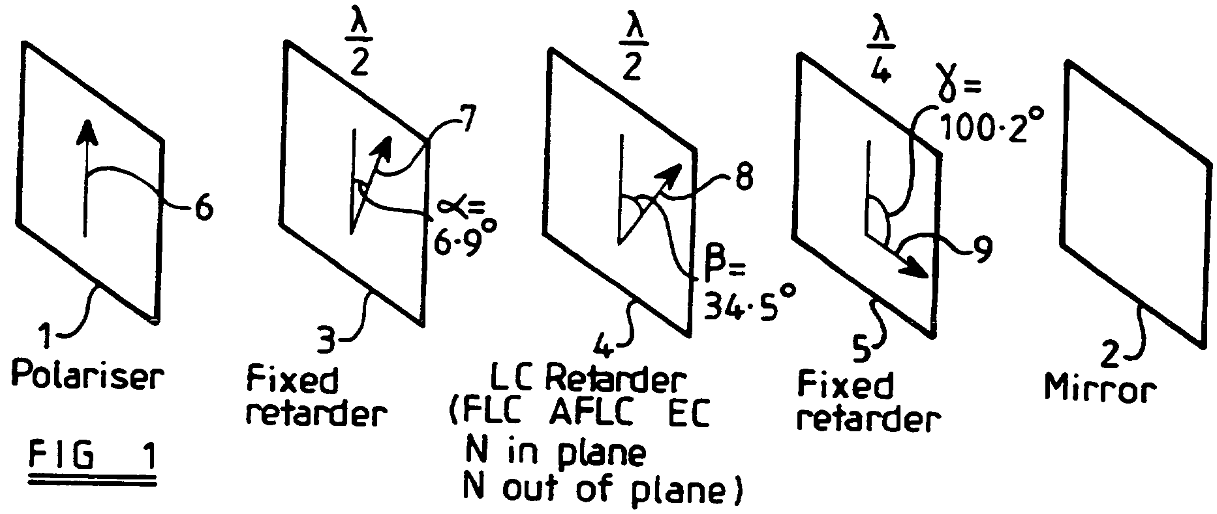
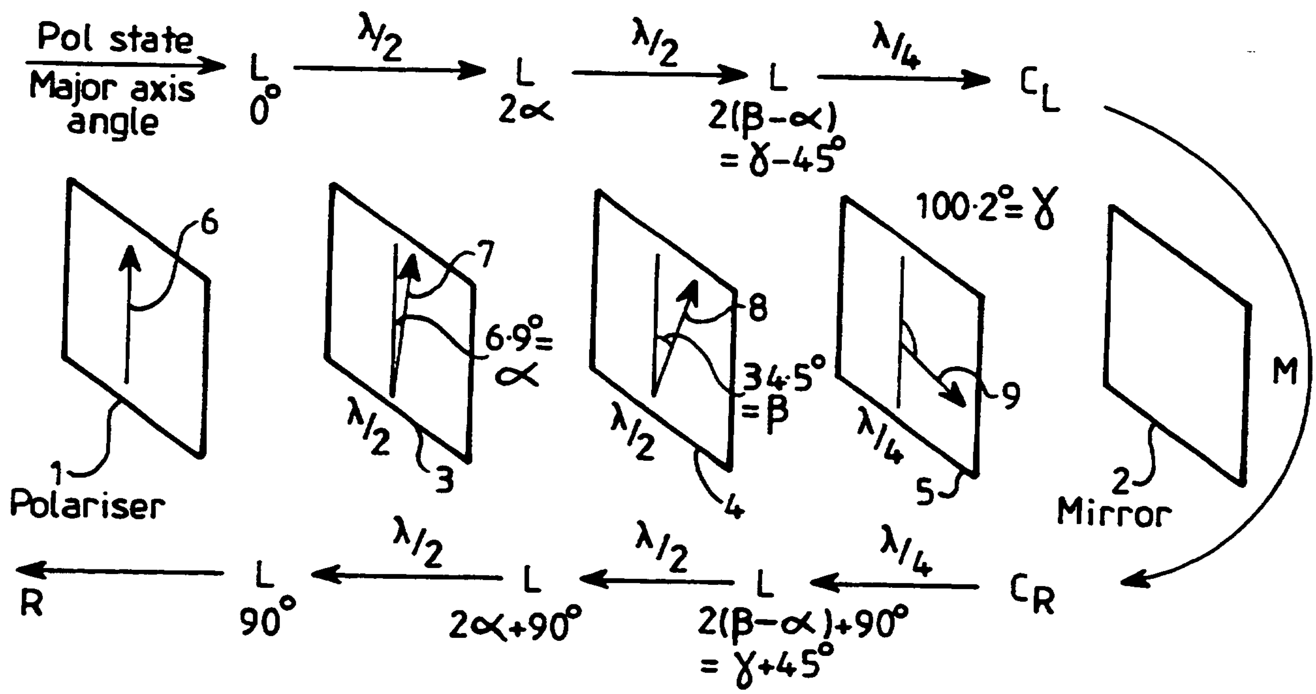

λ/2
λ/2
λ/4
γ=
100·2°
7
6
α=
6·9°
8
β=
34·5°
9
1
Polariser
3
Fixed
retarder
4
LC Retarder
(FLC AFLC EC
N in plane
N out of plane)
5
Fixed
retarder
2
Mirror

FIG 1

FIG 2


Pol state
Major axis
angle
L
0°
λ/2
L
2α
λ/2
L
2(β−α)
=γ−45°
λ/4
C_L
100·2°=γ
6
7
6·9°=
α
8
34·5°
=β
9
λ/2
3
λ/2
4
λ/4
5
M
1
Polariser
2
Mirror
R
L
90°
λ/2
L
2α+90°
λ/2
L
2(β−α)+90°
= γ+45°
λ/4
C_R

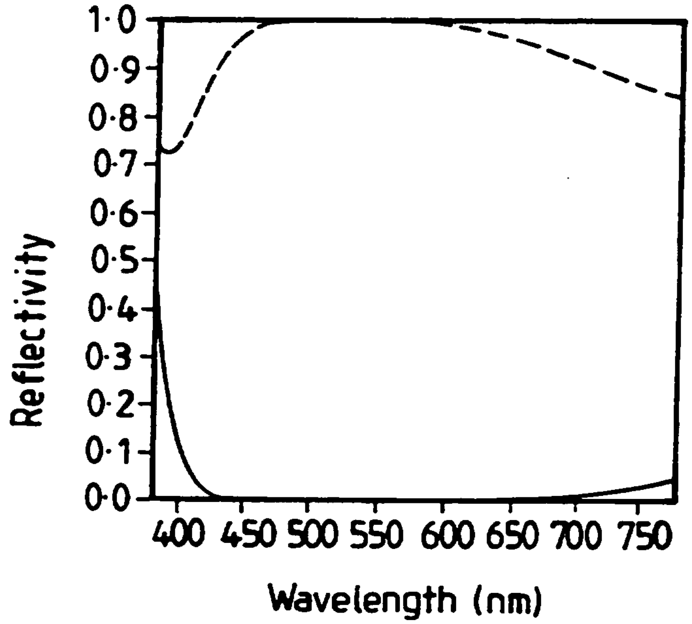

1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·0
Reflectivity
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 3

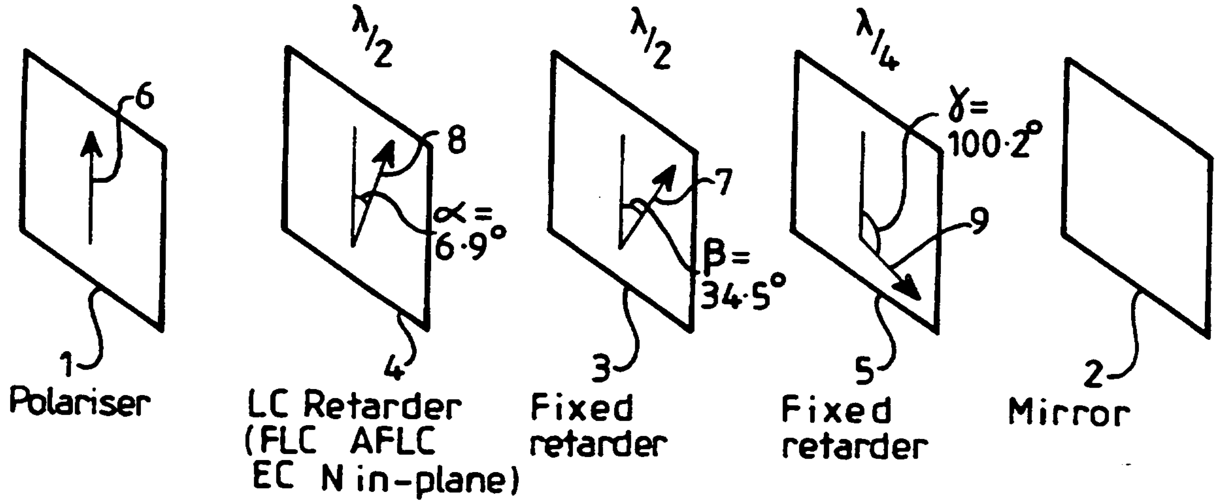

λ/2
λ/2
λ/4
6
8
α = 6·9°
7
β = 34·5°
γ = 100·2°
9
1 Polariser
4 LC Retarder (FLC AFLC EC N in-plane)
3 Fixed retarder
5 Fixed retarder
2 Mirror

FIG 4

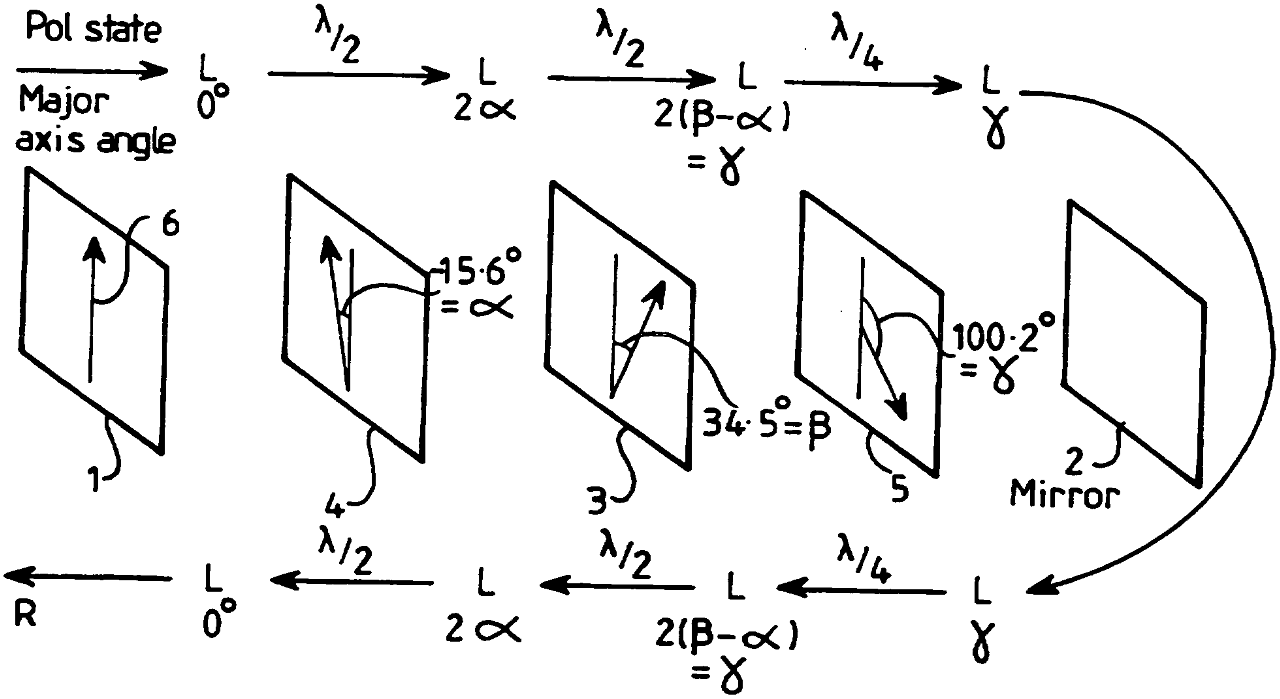

Pol state
Major axis angle
λ/2
λ/2
λ/4
L 0°
L 2∝
L 2(β−∝) = γ
L γ
6
15·6° = ∝
34·5° = β
100·2° = γ
1
4
3
5
2 Mirror
R
L 0°
L 2∝
L 2(β−∝) = γ
L γ
λ/2
λ/2
λ/4

FIG 5

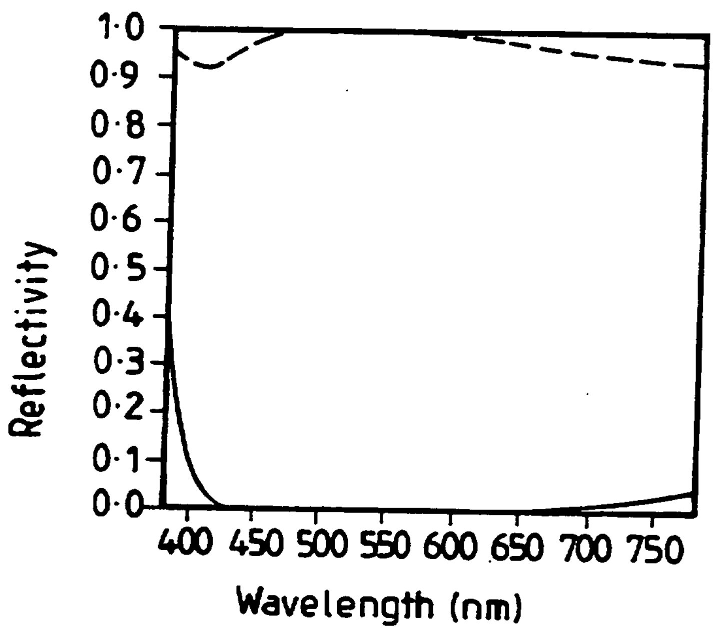
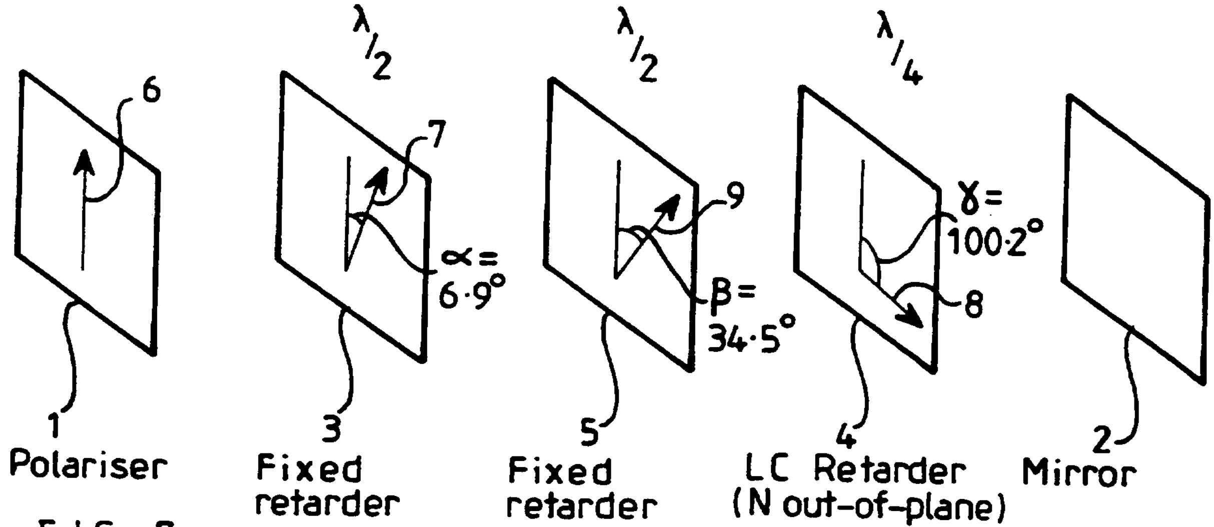
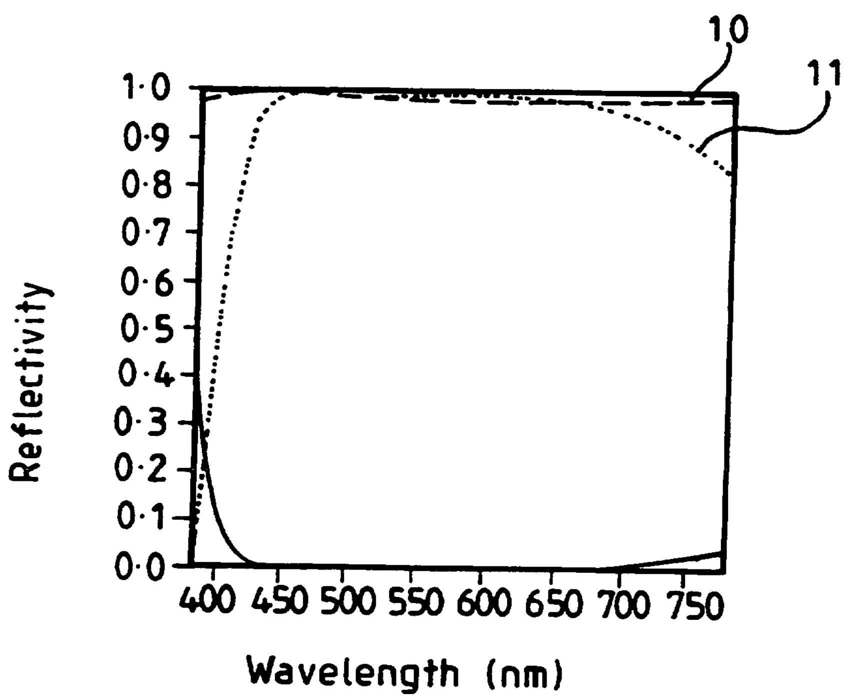

Reflectivity
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·0
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 6



λ/2
λ/2
λ/4
6
7
9
α = 6·9°
β = 34·5°
γ = 100·2°
8
1 Polariser
3 Fixed retarder
5 Fixed retarder
4 LC Retarder (N out-of-plane)
2 Mirror

FIG 7



10
11
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·0
Reflectivity
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 8

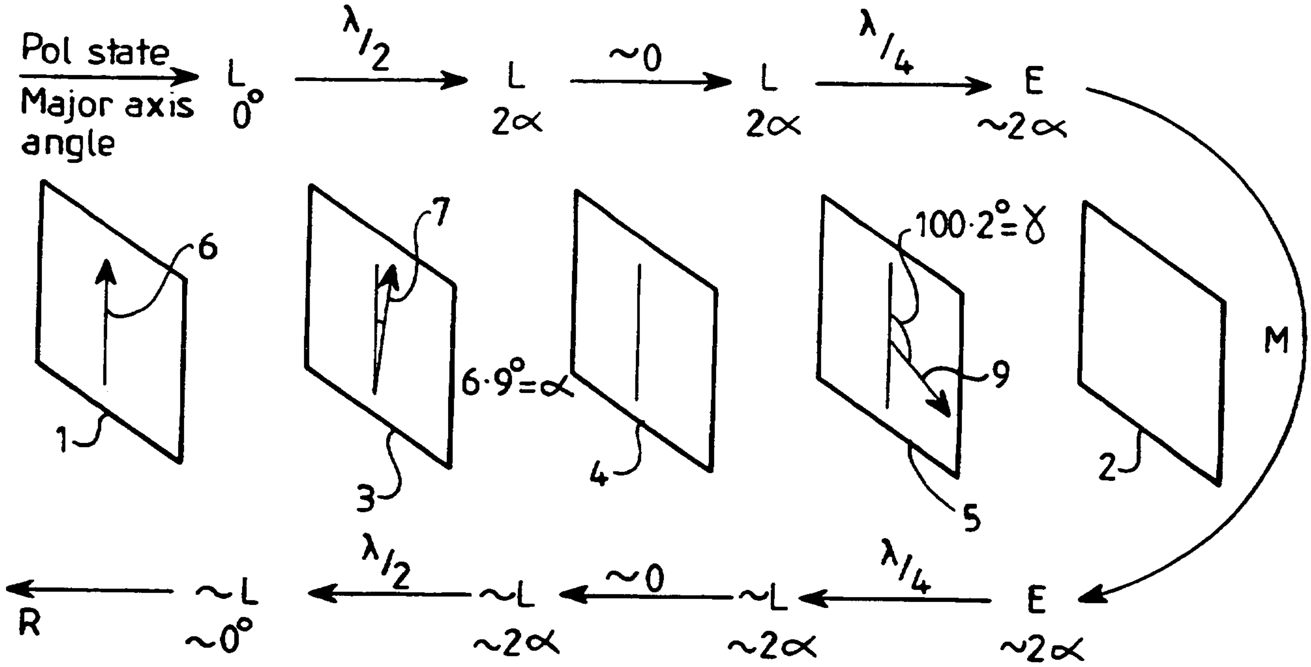

Pol state
Major axis angle
L
0°
$\lambda/2$
L
2∝
~0
L
2∝
$\lambda/4$
E
~2∝
6
7
6·9°=∝
100·2°=γ
9
M
1
3
4
5
2
R
~L
~0°
$\lambda/2$
~L
~2∝
~0
~L
~2∝
$\lambda/4$
E
~2∝

FIG 9

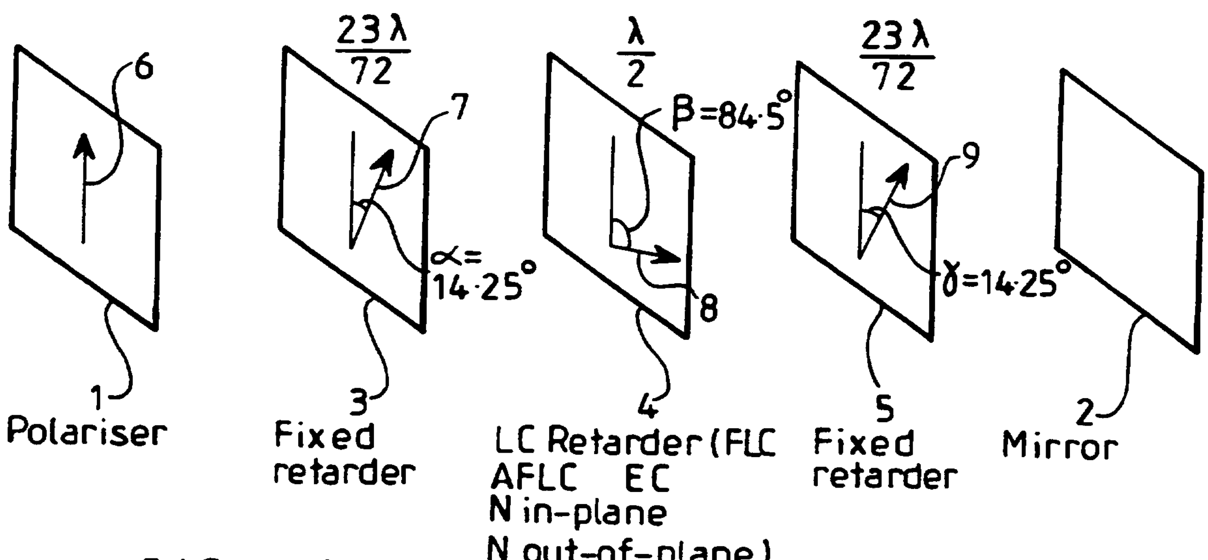

$\frac{23\lambda}{72}$
$\frac{\lambda}{2}$
$\frac{23\lambda}{72}$
6
7
β=84·5°
9
∝=
14·25°
8
γ=14·25°
1
Polariser
3
Fixed retarder
4
LC Retarder (FLC
AFLC EC
N in-plane
N out-of-plane)
5
Fixed retarder
2
Mirror

FIG 10

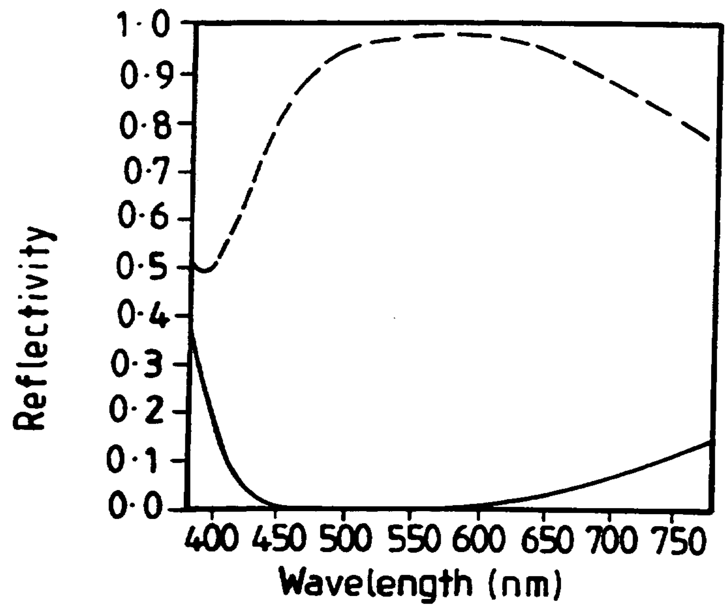
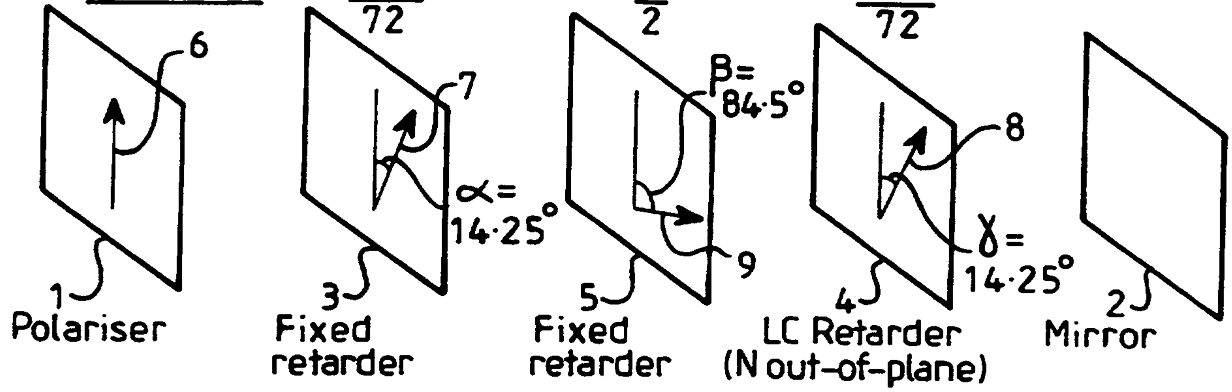


FIG 11

FIG 12



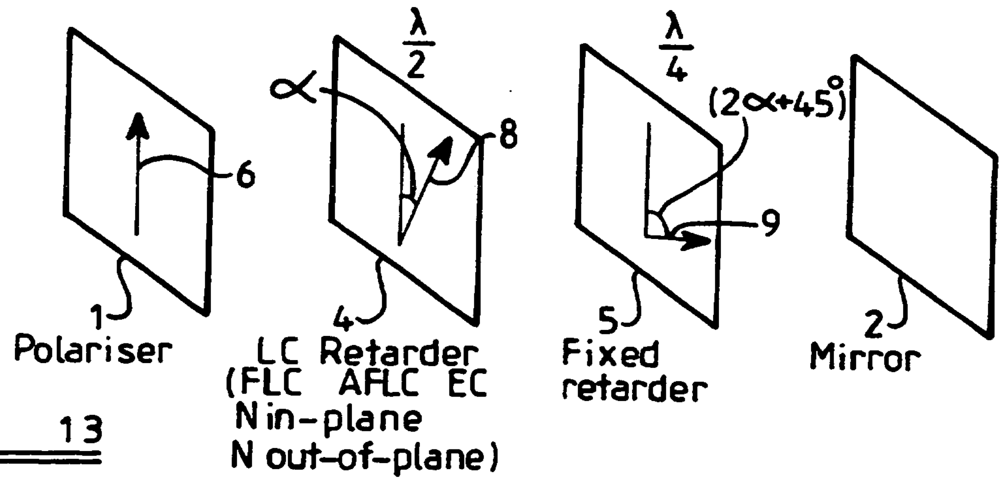


FIG 13

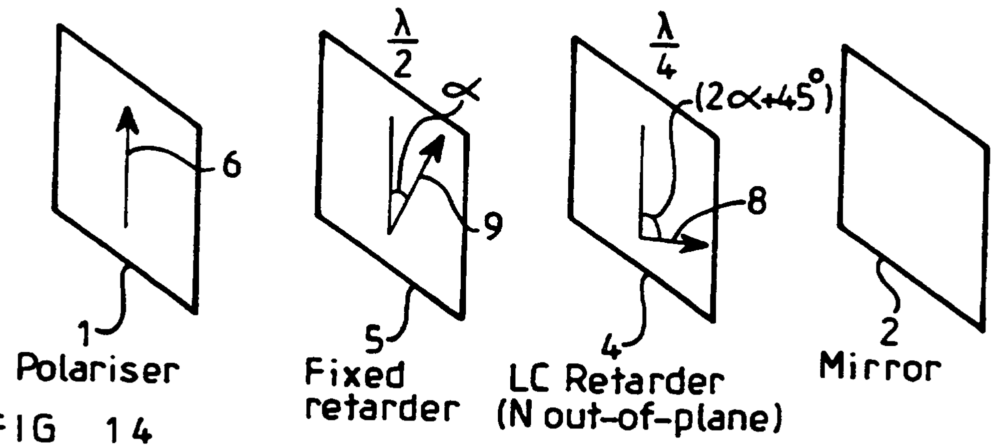


FIG 14

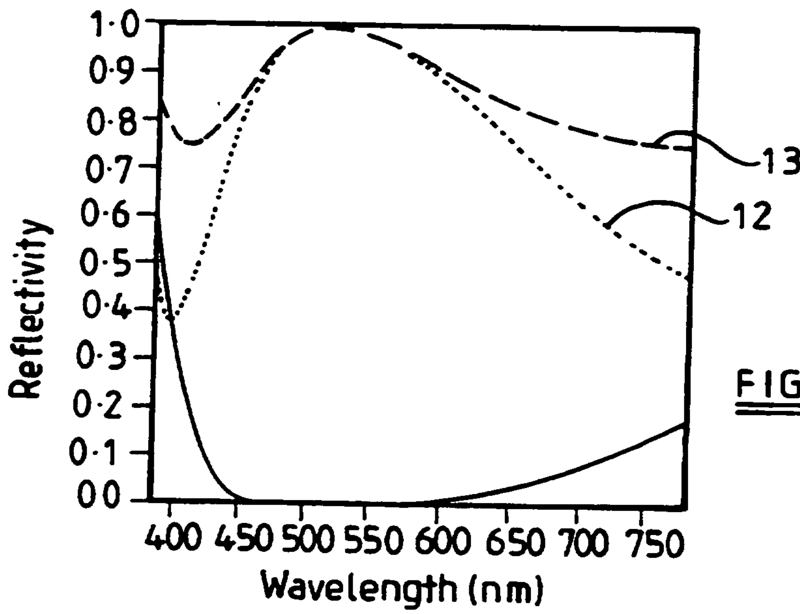


FIG 15

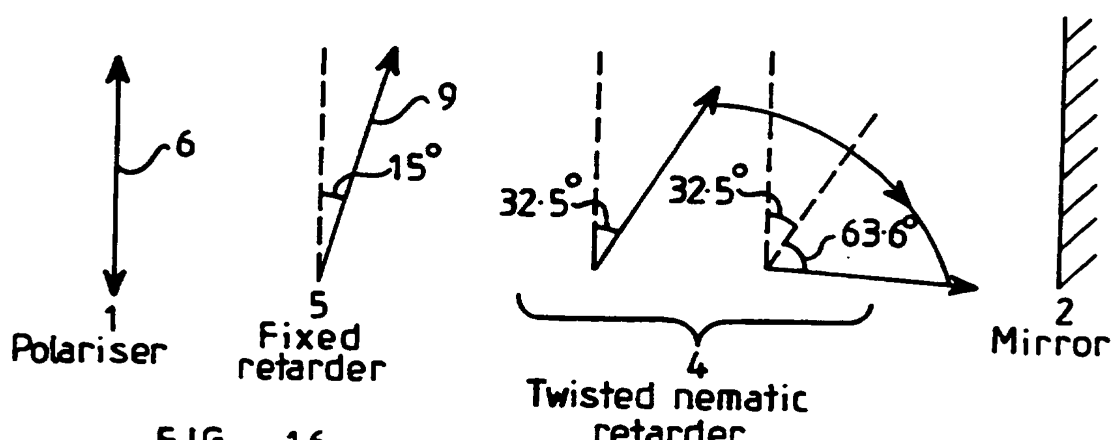


FIG 16

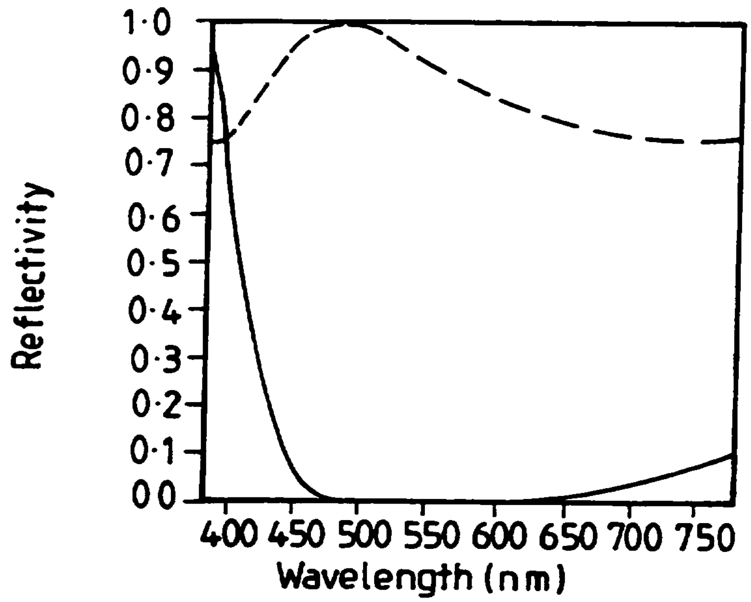

1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0 0
Reflectivity
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 17

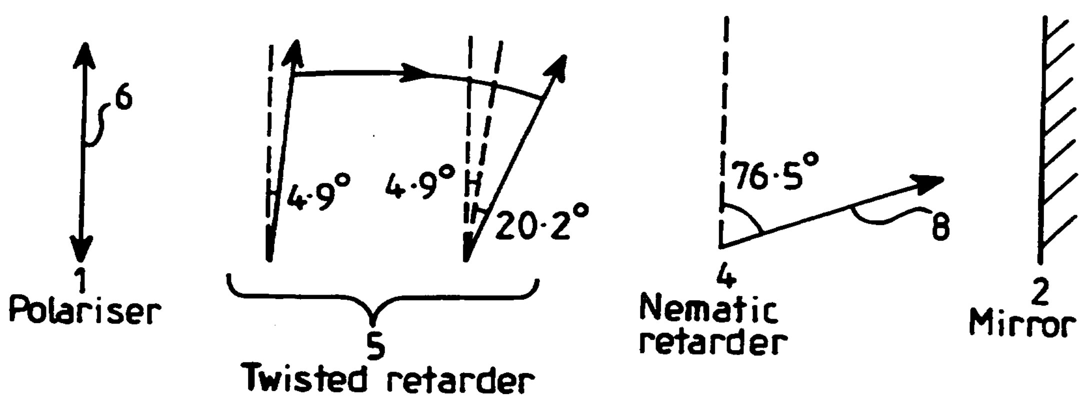

6
4·9°
4·9°
20·2°
76·5°
8
1
Polariser
5
Twisted retarder
4
Nematic retarder
2
Mirror

FIG 18

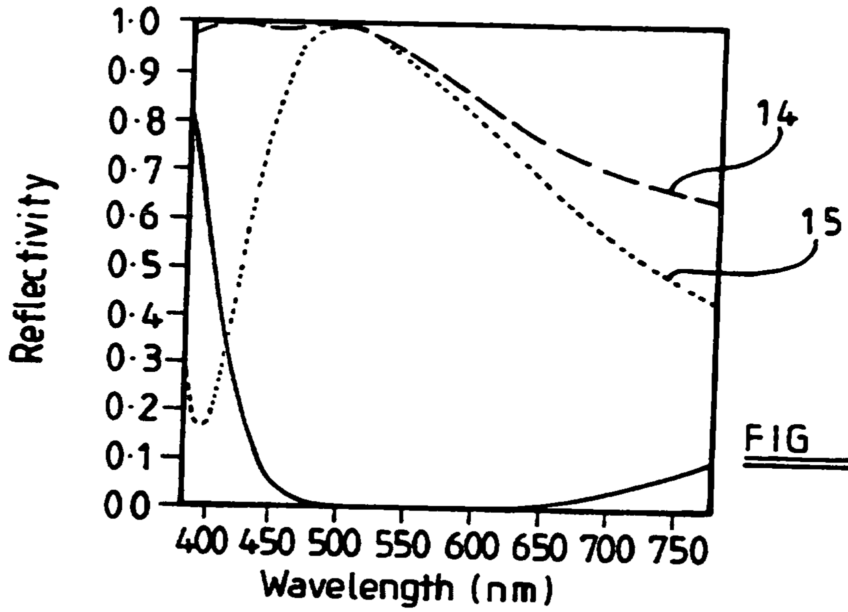

1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0 0
Reflectivity
400 450 500 550 600 650 700 750
Wavelength (nm)
14
15

FIG 19

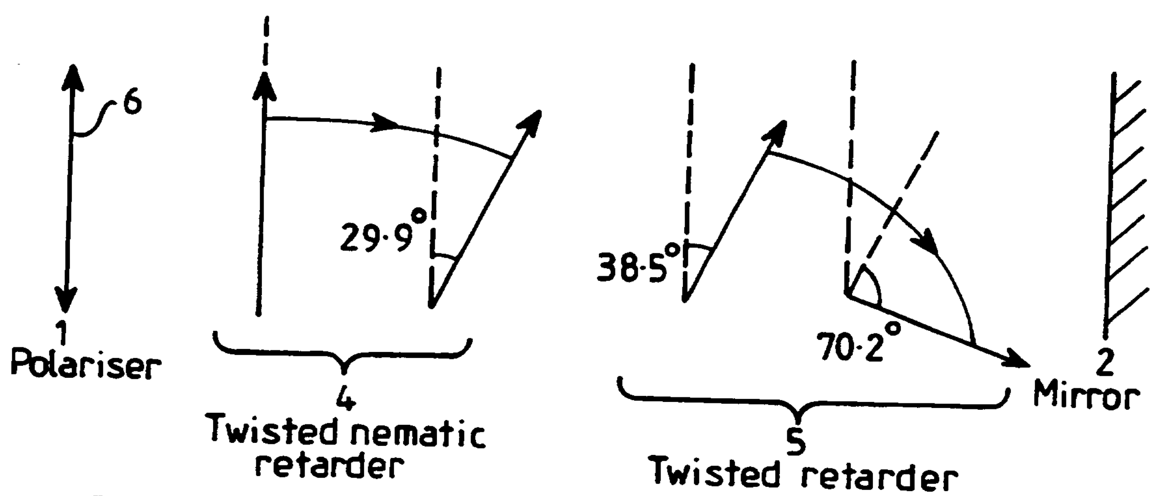
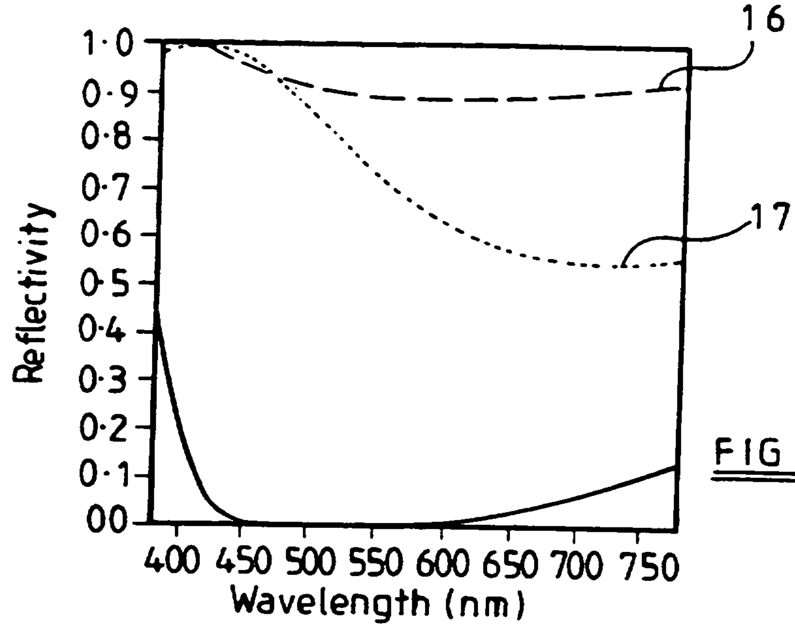

6
29·9°
38·5°
70·2°
1
Polariser
4
Twisted nematic retarder
5
Twisted retarder
2
Mirror

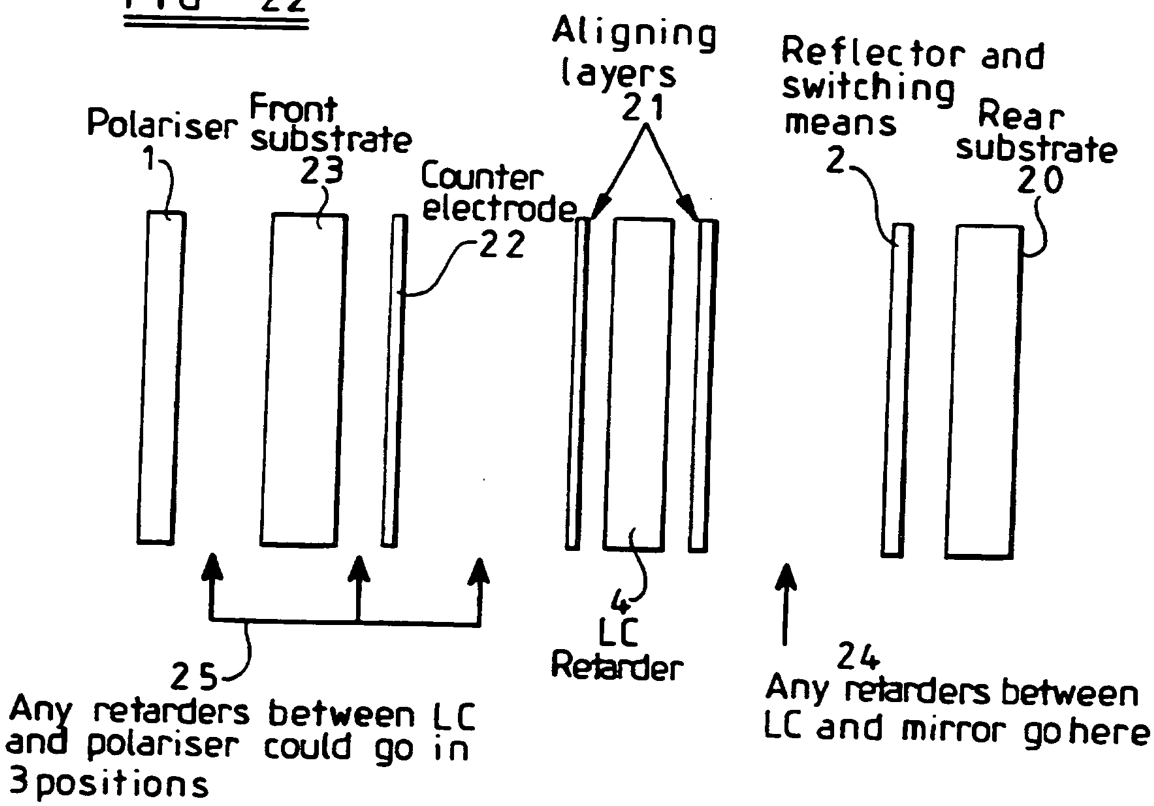
FIG 20



16
17
Reflectivity
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
00
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 21

FIG 22



Polariser
1
Front substrate
23
Counter electrode
22
Aligning layers
21
Reflector and switching means
2
Rear substrate
20
4
LC Retarder
25
Any retarders between LC and polariser could go in 3 positions
24
Any retarders between LC and mirror go here

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REFLECTIVE LIQUID CRYSTAL DEVICE.

The present invention relates to a reflective liquid crystal device. Such devices may be used, for instance, in hand-held and laptop equipment such as computers, diaries and personal organisers.

Proc. Ind. Acad. Sci., 1955, 41A 130 and 137 disclose circular polarisers and quarter waveplates made of combinations of birefringent plates to provide improved achromaticity. The individual retarders are combined with different azimuthal orientations of their optic axes to achieve the improvement in achromatic performance.

Seki et al, Mol. Cryst. Liq. Cryst., 1995, 263, 499 and Seiki et al, Eurodisplay, 1996, 464 disclose a liquid crystal device (LCD) of the reflective electrically controlled birefringence (ECB) type comprising a nematic liquid crystal and a quarter waveplate. The optic axis of the quarter waveplate is crossed with that of the nematic liquid crystal and is at 45° to a polariser disposed on one side of the nematic liquid crystal. The untwisted liquid crystal and quarter waveplate are disposed between the polariser and a mirror and a normally white state is achieved with the liquid crystal providing a retardation of $\lambda/4$. A black state is achieved by controlling the liquid crystal so as to provide zero retardation. This black state is effectively provided by the quarter waveplate and is achromatic only to the degree that the quarter waveplate is achromatic. A further retarder of negative birefringence with its optic axis perpendicular to its plane may be included to improve viewing angle performance.

Uchida et al, Asia Display, 1995, 599 discloses a reflective display in which a polariser and a mirror are disposed on opposite sides of a Hybrid Aligned Nematic Liquid Crystal Layer and a Retarder. The retarder is biaxial having an optic axis out of the plane to improve viewing angle and an in-plane optic axis which cooperates with the retardation of the liquid crystal layer to provide black and white states. The retarder in-plane axis is at 45° to the polarising axis of the polariser and is crossed with the optic axis of the liquid crystal layer. A normally black state is provided when the net retardation of the liquid crystal layer and the retarder is equal to $\lambda/4$. A white state is provided when the retardation of the liquid crystal is such that it cancels the retardation of the retarder. Such a display depends for its achromaticity on optimising the dispersion of the optical elements.

Ishinabe et al, Eurodisplay, 1996, 119 discloses a full colour reflective LCD in which a HAN liquid crystal layer and a biaxial retarder are disposed between a linear polariser and a mirror. The optic axis of the HAN layer is crossed with the optic axis of the retarder and is at 45° to the polarising axis of the polariser. A normally black state is achieved by making the difference between the retardations of the liquid crystal layer and the retarder equal to $\lambda/4$. Achromaticity is improved by adjusting the dispersion of materials of the liquid crystal layer and the retarder so that the birefringences partially compensate each other.

Kuo et al, Asia Display, 1995, 135 also discloses an LCD in which a HAN liquid crystal layer and a biaxial retarder are disposed between a linear polariser and a mirror. A dark state is provided when the total retardation is equal to an odd number of quarter wavelengths. The retarder has an in-plane optic axis which is crossed with the liquid crystal

axis and is at 45° to the polariser axis. The display may be operated in the normally black mode, as described hereinbefore, or in the normally white mode, in which case a larger passive retarder is used. Achromaticity may be improved by optimising the dispersion of the elements or by adjusting the dispersion so that the birefringences compensate each other.

Wu et al, Applied Physics Letters, 1996, 68, 1455 discloses a reflective LCD in which a twisted nematic liquid crystal cell and a retarder are disposed between a polariser and a mirror. The twisted nematic liquid crystal cell has a twist angle of 90°, is relatively thin, and has its input director angled at 20° to the axis of the polariser. The retarder provides a retardation of $\lambda/4$ and has an optic axis angled at 45° to the polariser axis. The cell operates in the normally white mode where the retardations of the liquid crystal cell and the retarder cancel each other in the white state and the black state is obtained by reducing the retardation of the liquid crystal cell to zero. Accordingly, the achromaticity depends on the achromaticity of the retarder.

Kuo et al, Eurodisplay, 1996, 387 discloses a similar twisted nematic display which is operated in the normally white mode and again achieves a black state whose achromaticity depends on the achromaticity of the retarder.

Fukuda et al disclose in three papers (IDRC, 1994, 201; SID Journal, 1995, 3, 83; Asia Display 1995, 881) a reflective supertwisted nematic (STN) LCD comprising a single polariser and a single retardation film. The twist of the liquid crystal is between 220 and 260° and the device operates in the normally white mode. STN liquid crystal is used to allow

high multiplex ratios i.e. small voltage differences between on and off voltages and hence a large value of dΔn of the liquid crystal, for instance greater than 0.6 micrometers. Achromaticity is improved by varying the dispersive properties of the liquid crystal and the retarder.

According to a first aspect of the invention, there is provided a reflective liquid crystal device as defined in the appended Claim 1.

According to a second aspect of the invention, there is provided a reflective liquid crystal device as defined in the appended Claim 19.

According to a third aspect of the invention, there is provided a reflective liquid crystal device as defined in the appended Claim 33.

Preferred embodiments of the invention are defined in the other appended claims.

It is thus possible to provide an LCD which is suitable for use in reflective displays. High brightness and contrast are achieved in a reflective single polariser device which has a wide viewing angle and a fast response speed. For instance, it is possible to achieve an azimuthal viewing angle of greater than plus and minus 80° without contrast inversion and in all azimuthal directions. It is further possible to achieve a black state having a degree of achromaticity which is substantially improved compared with known displays of the single polariser and reflector type. The optic axes of the retarders are oriented such that the combinations gives a retardation of $\lambda/4$ for the input polarised light from the polariser over a wide range of wavelengths in the non-reflective or dark state. The dark state is therefore very dark and achromatic and this

in turn gives high contrast when combined with the white state, which is also high brightness. It is further possible to achieve a good achromatic reflective or white state. The retarders need not be made of the same material and the dispersive properties of the retarder materials are not substantially important for achieving achromaticity, although the best display is obtained by using identical materials of as low dispersion as possible.

Thus, a high brightness device is provided because of the use of a single polariser. Good achromatic behaviour permits high contrast to be achieved. The use of optically thin layers permits a wide viewing angle.

The present invention will be further described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is an exploded diagrammatic view of a reflective LCD constituting a first embodiment of the invention;

Figure 2 corresponds to Figure 1 but illustrates the polarisation states for the display of Figure 1 in the black or non-reflective state;

Figure 3 is a graph of reflectivity against wavelength in nanometres illustrating the performance of the display of Figure 1 using an antiferroelectric liquid crystal layer;

Figure 4 is a view similar to Figure 1 of another display constituting a second embodiment of the invention;

Figure 5 illustrates the polarisation states for operation of the display of Figure 4 in a white or reflective state;

Figure 6 is a graph similar to Figure 3 illustrating the performance of the display of Figure 4 for a ferroelectric liquid crystal;

Figure 7 is a view similar to Figure 1 of a display constituting a third embodiment of the invention;

Figure 8 is a graph similar to that of Figure 3 illustrating performance of the display of Figure 1 with a nematic out-of-plane liquid crystal;

Figure 9 illustrates polarisation states for the display of Figure 1 in which the liquid crystal layer is of the nematic out-of-plane type;

Figure 10 is a view similar to Figure 1 of a display constituting a fourth embodiment of the invention;

Figure 11 is a graph similar to Figure 3 showing the performance of the display of Figure 10 using antiferroelectric liquid crystal;

Figure 12 is a view similar to Figure 1 of a display constituting a fifth embodiment of the invention;

Figure 13 is a view similar to Figure 1 of a display constituting a sixth embodiment of the invention;

Figure 14 is a view similar to Figure 1 of a display constituting a seventh embodiment of the invention;

Figure 15 is a graph similar to Figure 3 showing the performance of the display of Figure 14;

Figure 16 is a schematic diagram of a display constituting an eighth embodiment of the invention;

Figure 17 shows a graph similar to Figure 3 illustrating the performance of the display of Figure 16;

Figure 18 is a view similar to that of Figure 16 of a display constituting a ninth embodiment of the invention;

Figure 19 shows a graph similar to that of Figure 3 illustrating performance of the display of Figure 18;

Figure 20 is a view similar to Figure 16 of a display constituting a tenth embodiment of the invention;

Figure 21 shows a graph similar to Figure 3 illustrating performance of the display of Figure 20; and

Figure 22 is an exploded schematic diagram illustrating the general construction of the displays shown in the preceding figures.

Like reference numerals refer to like parts throughout the drawings.

The reflective LCD shown in Figure 1 comprises a linear polariser 1, a polarisation-preserving reflector 2, a fixed retarder 3, a variable retarder 4, and a fixed retarder 5. The polariser has a polarisation axis 6 and the

fixed retarder 3 has an optic axis 7 at an angle α to the polarising axis 6. The fixed retarder 3 has a retardation such that it acts as a half waveplate at a wavelength λ at the middle of the visible spectrum. The middle wavelength of the visible spectrum is normally considered to be 550 nanometres but, in order to maximise the achromaticity of the black state of the LCD, λ is shifted slightly towards the blue end of the visible spectrum. A preferred value for λ is in the range of 510 to 550 nanometres.

The variable retarder 4 comprises a liquid crystal layer which has an optic axis 8 at an angle β to the polarising axis 6 in the "normal" state of the liquid crystal. The liquid crystal may comprise a ferroelectric liquid crystal (FLC) whose optic axis is switchable by + or -22.5° although -22.5° is preferred. Alternatively, the liquid crystal may comprise an antiferroelectric liquid crystal (AFLC) whose optic axis 8 has two orientations, namely ± 22.5° in the bright or reflective state of the device. Smectic liquid crystals other than FLC and AFLC may be used and another possibility for the liquid crystal is an electroclinic (EC) (Chiral Smectic A) liquid crystal, which provides grey scale capability by azimuthally controlled optic axis orientation. A further possibility for the liquid crystal is a nematic in-plane switching liquid crystal which also has an azimuthally controlled optic axis orientation. In each of these cases, the LC retarder 4 provides a fixed retardation of $\lambda/2$.

In an alternative embodiment, the retarder 4 comprises a nematic out-of-plane liquid crystal whose optic axis is switched in and out of the plane of the retarder so as to vary the retardation by a difference of $\lambda/2$ between the bright or reflective and dark or non-reflective states of the

LCD. It is preferred for the retardation to switch either between λ and $\lambda/2$ or between $\lambda/2$ and close to zero.

The fixed retarder 5 has an optic axis 9 at an angle γ to the polarising axis 6. The fixed retarders 3 and 5 may be made from any suitable anisotropic material, such as a liquid crystal polymer or a reactive mesogen which is cross-linked to form a polymer. The liquid crystal retarder 4, when of the nematic type, may be a Fredericks cell, a HAN cell, or a Pi cell.

The angles α, β and γ are related to each other in that $\beta = x\alpha$ and $\gamma = 2(\beta-\alpha) + 45°$. Preferred values are $\alpha = 6.9°$ and $x = 5$ which gives preferred values of 34.5° for β and 100.2° for γ.

Figure 2 illustrates the light path and polarisation states of light through the LCD of Figure 1 for the non-reflecting or dark state of the LCD at a wavelength λ which is the "design" wavelength of the retarders. Linear polarisations are indicated by "L", left handed circular polarisation is indicated by "C_L" and right handed circular polarisation is indicated by "C_R". Unpolarised light incident on the polariser 1 is linearly polarised with the polarisation vector at an angle of zero degrees to the polarising axis 6. The half waveplate formed by the fixed retarder 3 rotates the polarisation vector by 2α and the half waveplate formed by the retarder 4 further rotates the polarisation vector to γ-45°. The quarter waveplate formed by the retarder 5 converts the light to left handed circularly polarised which is converted by reflection by the mirror 2 to right handed circularly polarised light. The quarter waveplate 5 converts the light back to linearly polarised with the polarisation vector at an angle of $\gamma + 45°$. The half wave plate 4 rotates the polarisation vector to $2\alpha + 90°$

and the half waveplate 3 rotates the polarisation vector to 90°. The polarisation vector of the reflected light incident on the polariser 1 is orthogonal to the polarising axis 6 so that the reflected light is absorbed by the polariser 1.

The retardations provided by the retarders 3, 4 and 5 are not exactly $\lambda/2$ and $\lambda/4$ for wavelengths which differ from the "design" wavelength. Accordingly, the effects of the retarders 3, 4 and 5 differ slightly from the description given hereinbefore. However, the angles α, β and γ of the optic axes 7, 8 and 9 are such that the polarisation vector of the light reflected back to the polariser 1 differs little from 90°. Thus, a good achromatic black state is provided by the LCD.

In order to provide a reflective or white state, the liquid crystal retarder 4 is switched so that the optic axis 8 rotates as described hereinbefore for the various types of liquid crystals. This results in the light reflected back to the polariser 1 having a polarisation vector which is at or close to zero degrees throughout the visible spectrum, thus giving a good achromatic white state.

Figure 3 is a graph of reflectivity against wavelength in nanometres illustrating the performance of the LCD of Figure 1 with the liquid crystal retarder 4 embodied by AFLC. The unbroken line illustrates reflectivity in the black state whereas the broken line illustrates reflectivity in the white state. Throughout most of the visible spectrum, the reflectivity in the black state is substantially equal to zero but rises at the blue and red extremes of the spectrum. The reflectivity rises more quickly at the blue end of the spectrum, which is why the "design" wavelength λ is chosen to be displaced towards the blue end compared with the actual centre of

the visible spectrum so as to improve the achromaticity of the black state. The reflectivity in the white state is a maximum throughout a substantial portion of the visible spectrum but falls towards the blue and red ends. However, a reasonably achromatic white state is achieved. Further, the difference between reflectivities in the black and white states throughout the spectrum is relatively high. A bright display with good contrast performance throughout the spectrum is therefore provided. Because the individual layers and the whole device is relatively thin, the device has a good range of viewing angles. In particular, a range of $\pm 80°$ of azimuth angle for all polar angles can be achieved without contrast inversion i.e. the dark state becoming brighter than the bright state.

The reflective LCD shown in Figure 4 differs from that shown in Figure 1 in that the liquid crystal retarder 4 is disposed between the polariser 1 and the fixed retarder 3 instead of between the fixed retarders 3 and 5. The liquid crystal retarder 4 may be embodied by FLC, AFLC, EC, and nematic in-plane liquid crystal. Operation in the dark or black state is substantially identical to that of the LCD of Figure 1 as illustrated in Figure 2.

Figure 5 illustrates operation of the LCD of Figure 4 in the bright or white state with the optic axis of the liquid crystal retarder 4 switched by -22.5° to be at -15.6° to the polarising axis 6. Unpolarised light incident on the polariser 1 is linearly polarised with a polarisation vector at zero degrees to the axis 6. The polarisation vector is rotated by the retarder 4 to 2α and is further rotated by the retarder 3 to γ. The polarisation vector is unaffected by passage of the light both ways through the retarder 5 and by reflection at the mirror 2 so that the reflected light is

incident on the retarder 3 with a polarisation vector at an angle of γ. the retarder 3 rotates the polarisation vector to 2α and the retarder 4 rotates the polarisation vector to zero degrees. The polarisation vector of the light reflected back to the polariser 1 is therefore parallel to the polarising axis 6 and the reflected light thus returns out of the LCD substantially unattenuated.

The performance of the LCD of Figure 4 is shown in Figure 6. The reflectivity in the dark state is substantially identical to that illustrated in Figure 3 and the reflectivity in the bright state is improved with respect that shown in Figure 3 so that the brightness and achromaticity are slightly improved together with the contrast ratio between the states throughout the visible spectrum.

The LCD shown in Figure 7 differs from that shown in Figure 1 in that the variable liquid crystal retarder 4 forms the quarter waveplate adjacent the mirror 2. The retarder 4 is embodied as a nematic out-of-plane liquid crystal whose optic axis 8 is switchable in and out of the plane of the retarder 4 to vary the retardation between two values which differ from each other by $\lambda/4$. It is preferred for the retardation to be switched between $\lambda/2$ and $\lambda/4$ or between $\lambda/4$ and substantially zero.

Figure 9 illustrates operation of the LCD of Figure 1 in the bright state when the retarder 4 is embodied as a nematic out-of-plane liquid crystal. In this mode of operation, the retarder 4 provides close to zero retardation or $\lambda/2$ retardation and has substantially no effect on the passage of light. Unpolarised light incident on the polariser 1 is linearly polarised to have a polarisation vector at zero degrees to the polarising axis 6. The retarder 3 rotates the polarisation vector to 2α which passes

through the retarder 4 with little or no change. The retarder 5 converts the light to slightly elliptically polarised (E) with the major axis at 2α to the polarising axis 6. The elliptically polarised light is reflected by the mirror 2 without substantially affecting its state of polarisation. The light is therefore converted by the retarder 5 to substantially linearly polarised light with the polarisation vector at substantially 2α. The retarder 4 has no effect so that the retarder 3 rotates the polarisation vector to substantially zero degrees with respect to the polarising axis 6. The reflected light is thus transmitted by the polariser 1.

The performance of the LCD whose operation is illustrated in Figure 9 is represented by the curves 10 and 11 in Figure 8. The curve 10 is for $\lambda/4$ to ~0 whereas the curve 11 is for $\lambda/4$ to $\lambda/2$. A display of high contrast and brightness with good achromatic bright and dark states is provided.

In the displays shown in Figures 1, 4 and 7, the combination of the retarders 3, 4 and 5 together with the linear polariser 1 in the dark state acts like a circular polariser. In the display shown in Figure 10, combination of the retarders 3, 4 and 5 act as a quarter waveplate. The fixed retarder 3 acts as a $23\lambda/72$ waveplate whose optic axis α is at 14.25° to the polarising axis 6 of the polariser 1. The variable liquid crystal retarder 4 acts, in the dark state, as a half waveplate whose optic axis 8 is at 84.5° to the polarising axis 6. The fixed retarder 5 is substantially identical to the fixed retarder 3. The variable retarder 4 may be embodied by FLC, AFLC, EC, and nematic in-plane liquid crystal providing a fixed retardation of $\lambda/2$ but with the optic axis 8 switchable by + or - 22.5° between the bright and dark states of the LCD. When embodied by nematic out-of-plane liquid crystal, the optic axis of the retarder 4 is switchable in and of the plane of the retarder and the

retardation is switchable between states which differ by $\lambda/2$, preferably between $\lambda/2$ and zero or between λ and $\lambda/2$.

As shown in Figure 11, the LCD of Figure 10 also provides good performance in terms of achromaticity of dark and bright states, brightness and contrast ratio throughout the visible spectrum.

The LCD of Figure 12 differs from that shown in Figure 10 in that the variable liquid crystal retarder 4 is disposed adjacent the mirror 2. The retarder 4 is embodied as a nematic out-of-plane liquid crystal whose optic axis 8 switches in and out of the retarder plane so as to vary the retardance between $23\lambda/72$ and $23\lambda/324$ or between $23\lambda/72$ and $46\lambda/81$ to give linear polarisation states at the mirror 2.

The LCD of Figure 13 differs from that of Figure 1 in that only two retarders are disposed between the polariser 1 and the mirror 2. The first retarder comprises a variable liquid crystal retarder 4 which may be embodied by FLC, AFLC, EC, nematic in-plane liquid crystal and nematic out-of-plane liquid crystal as described hereinbefore. The optic axis 8 is at an angle α to the polarising axis 6 of the polariser 1. In the black state, the retarder 4 acts as a half waveplate.

The fixed retarder 5 acts as a quarter waveplate and has an optic axis 9 at an angle of $(2\alpha+45°)$ to the polariser axis 6. Although the optimum value for α in terms of achromaticity of the display is 15°, this optimum angle is not available for all embodiments of the liquid crystal retarder 4. Thus, a value of 22.5° is normally chosen for α. Operation of the retarder 4 is then as described hereinbefore for the different liquid crystal embodiments.

Figure 14 shows an LCD which differs from that shown in Figure 13 in that the liquid crystal retarder 4 is now disposed adjacent the mirror 2. The retarder 4 comprises a nematic out-of-plane liquid crystal and operates as described hereinbefore with reference to Figure 7.

The performances of the LCD shown in Figure 14 is illustrated in Figure 15. The dark state reflectivity is substantially identical for both LCDs of Figures 13 and 14 and, although not as good as the "three retarder" devices described hereinbefore, nevertheless provides a good achromatic black state. Curve 12 illustrates the bright state performance of Figure 14 with the liquid crystal at a retardation of $\lambda/2$ whereas curve 13 illustrates the bright state performance of the LCD of Figure 14 with the liquid crystal at a retardation of 0. Bright displays of good contrast ratio and good achromaticity are provided and give extended viewing angles.

The LCD shown in Figure 16 comprises a two retarder device in which the first retarder 5 is fixed with its optic axis 9 at 15° to the polarising axis 6 of the polariser 1. The retarder 5 has a thickness of 1168 nanometres and is made of RM 257 available from Merck. The twisted nematic retarder 4 comprises a chiral retarder having a twist of 63.6° with its input director at an angle of 32.5° to the polariser axis 6. The fixed retarder 5 has an optical thickness ($d.\Delta n$) of 227 nanometres.

In the light state, the retarder 4 is switched to provide close to zero retardation.

Figure 17 illustrates the reflectivity of the LCD of Figure 16.

The LCD shown in Figure 18 comprises a fixed twisted retarder 5 and a nematic out-of-plane liquid crystal retarder 4 disposed between the polariser 1 and the mirror 2. The retarder 5 has an input director at an angle of 4.9° to the polariser axis 6 and a twist angle of 20.2°. The retarder 5 is made of RM 257 and has a thickness of 1690 nanometres.

The nematic retarder 4 has a thickness of 600 nanometres for material with the same birefringence as RM 257 and an optic axis at 76.5° to the polariser axis 6 in the dark state. The retarder is switched to either twice the optical thickness, corresponding to a half wave retardation, or to zero optical thickness, corresponding to zero retardation, to switch the device to the bright state.

The performance of the LCD shown in Figure 18 is illustrated by Figure 19. The bright state for the retarder switched to zero retardation is illustrated by curve 14 and for the retarder 4 switched to the half wave retardation by curve 15.

The LCD shown in Figure 20 comprises two twisted retarders 4 and 5 between the polariser 1 and the mirror 2. The retarder 4 comprises a nematic liquid crystal whose input director is aligned with the polarising axis 6 of the polariser 1. The retarder 4 has a twist of 29.9° and a thickness of 1586 nanometres when made of RM 257 type material. The fixed twisted retarder 5 has an input director at an angle of 38.5° to the polarising axis 6, a twist of 70.2° and a thickness of 658 nanometres when made of RM 257.

Figure 21 illustrates the performance of the LCD of Figure 20. The curve 16 represents the bright state performance whereas the curve 17

represents the bright state performance of a device which differs from that shown in Figure 20 in that the retarder adjacent the polariser is fixed and the retarder adjacent the mirror is switchable. For the device shown in Figure 20, the bright state is obtained by switching the retardation of the retarder 4 to substantially zero.

Figure 22 illustrates the construction of an LCD of any of the types described hereinbefore. The reflector 2 is incorporated with switching means and formed on a rear substrate 20. For instance, the reflector may be electrically conductive and may be pixellated so as to provide individual picture element (pixel) electrodes for addressing a pixellated device. Active or passive matrix addressing electronics may be formed on the rear substrate for addressing the pixels of the LCD.

The liquid crystal retarder 4 is associated with aligning layers 21 and is provided with a transparent counterelectrode 22 which may be continuous and may be formed of indium tin oxide (ITO). A transparent front substrate 23 is provided and may be formed of glass or plastics. The polariser 1 is shown outside the substrate 23 but may be formed inside the substrate.

If any fixed retarders are required between the liquid crystal retarder 4 and the reflector 2, they may be located in the position indicated by arrow 24. The gap between the liquid crystal retarder 4 and the reflector 2 should be minimised so as to avoid undesirable parallax effects, for instance in the case pixellated devices. If any fixed retarders are required between the polariser 1 and the liquid crystal retarder 4, they may be provided in any of the three positions indicated by arrows 25.

Any of the fixed retarders may be made biaxial or an additional fixed retarder whose optic axis is parallel to an axis substantially perpendicular to the plane of the device may be provided to improve the viewing angle of the device.

CLAIMS

1. A reflective liquid crystal device comprising a linear polariser, a polarisation preserving reflector, and a retarder arrangement comprising at least three retarders, a first of which is disposed between the polariser and the reflector, a second of which is disposed between the first retarder and the reflector, and a third of which is disposed between the second retarder and the reflector, at least one of the first, second and third retarders comprising a liquid crystal layer which is switchable between a non-reflective device state, in which the retardation of the retarder arrangement is equal to $(2n+1)\lambda/4$ where n is an integer and λ is a wavelength of visible light, and a reflective device state.

2. A device as claimed in Claim 1, in which, in the non-reflective device state, the first retarder has a retardation of substantially $\lambda/2$, the second retarder has a retardation of substantially $\lambda/2$, and the third retarder has a retardation of substantially $\lambda/4$.

3. A device as claimed in Claim 2, in which, in the non-reflective device state, the optic axis of the first retarder is substantially at an angle α to the polarisation axis of the polariser, the optic axis of the second retarder is substantially at an angle of $x\alpha$ to the polarisation axis, and the optic axis of the third retarder is substantially at an angle of $2(\beta-\alpha)+45°$ to the polarisation axis.

4. A device as claimed in Claim 3, in which α is substantially equal to 6.9°.

5. A device as claimed in Claim 3 or 4, in which x is substantially equal to 5.

6. A device as claimed in any one of Claims 2 to 5, in which the first or second retarder comprises the liquid crystal layer whose optic axis rotates by an angle substantially equal to 22.5° about the normal direction of light passage during switching.

7. A device as claimed in any one of Claims 2 to 5, in which the second retarder comprises the liquid crystal layer and has a retardation which is switchable between substantially $p\lambda/2$ and substantially $(p+1)\lambda/2$, where p is an integer.

8. A device as claimed in Claim 7, in which p is equal to zero or one.

9. A device as claimed in any one of Claims 2 to 5, in which the third retarder comprises the liquid crystal layer and has a retardation which is switchable between substantially $q\lambda/4$ and substantially $(q+1)\lambda/4$, where q is an integer.

10. A device as claimed in Claim 9, in which q is equal to zero or one.

11. A device as claimed in any one of Claims 7 to 10, in which the liquid crystal layer is an out-of-plane switching nematic liquid crystal.

12. A device as claimed in Claim 1, in which, in the non-reflective device state, the first retarder has a retardation of $23\lambda/72$, the second

retarder has a retardation of $\lambda/2$, and the third retarder has a retardation of $23\lambda/72$.

13. A device as claimed in Claim 12, in which, in the non-reflective device state, the optic axis of the first retarder is at an angle of substantially 14.25° to the polarisation axis of the polariser, the optic axis of the second retarder is at an angle of substantially 84.5° to the polarisation axis, and the optic axis of the third retarder is at an angle of substantially 14.25° to the polarisation axis.

14. A device as claimed in Claim 12 or 13, in which the second retarder comprises the liquid crystal layer whose optic axis rotates by an angle substantially equal to 22.5° about the normal direction of light passage during switching.

15. A device as claimed in Claim 12 or 13, in which the second retarder comprises the liquid crystal layer and has a retardation which is switchable between substantially $r\lambda/2$ and substantially $(r+1)\lambda/2$, where r is an integer.

16. A device as claimed in Claim 15, in which r is equal to zero or one.

17. A device as claimed in Claim 12 or 13, in which the third retarder comprises the liquid crystal layer and has a retardation which is switchable between substantially $23\lambda/72$ and substantially $23\lambda/324$ or substantially $46\lambda/81$.

18. A device as claimed in any one of Claims 15 to 17, in which the liquid crystal layer is an out-of-plane switching nematic liquid crystal.

19. A reflective crystal device comprising a linear polariser, a polarisation preserving reflector, and a retarder arrangement comprising a first retarder disposed between the polariser and the reflector and a second retarder disposed between the first retarder and the reflector, at least one of the first and second retarders comprising an untwisted liquid crystal layer which is switchable between a non-reflective device state, in which the retardation of the retarder arrangement is equal to $(2n+1)\lambda/4$ where n is an integer and λ is a wavelength of visible light, and a reflective device state.

20. A device as claimed in Claim 19, in which, in the non-reflective device state, the first retarder has a retardation of substantially $\lambda/2$ and the second retarder has a retardation of substantially $\lambda/4$.

21. A device as claimed in Claim 20, in which, in the non-reflective device state, the optic axis of the first retarder is substantially at an angle α to the polarisation axis of the polariser and the optic axis of the second retarder is substantially at an angle of $2\alpha+45°$ to the polarisation axis.

22. A device as claimed in Claim 21, in which α is substantially equal to 15°.

23. A device as claimed in Claim 21, in which α is substantially equal to 22.5° and the first retarder comprises the liquid crystal layer whose optic axis rotates by an angle substantially equal to 22.5° about the normal direction of light passage during switching.

24. A device as claimed in any one of Claims 6, 14 and 23, in which the liquid crystal layer is a ferroelectric liquid crystal.

25. A device as claimed in any one of Claims 6, 14 and 23, in which the liquid crystal layer is an antiferroelectric liquid crystal.

26. A device as claimed in any one of Claims 6, 14 and 23, in which the liquid crystal layer is an electroclinic liquid crystal.

27. A device as claimed in any one of Claims 6, 14 and 23, in which the liquid crystal layer is an in-plane switching nematic liquid crystal.

28. A device as claimed in Claim 21, in which α is substantially equal to 15° and the first retarder comprises the liquid crystal layer having a retardation which is switchable between substantially $p\lambda/2$ and substantially $(p+1)\lambda/2$, where p is an integer.

29. A device as claimed in Claim 28, in which p is equal to zero or one.

30. A device as claimed in Claim 21 or 22, in which the second retarder comprises the liquid crystal layer and has a retardation which is switchable between substantially $q\lambda/4$ and substantially $(q+1)\lambda/4$, where q is an integer.

31. A device as claimed in Claim 30, in which $q=0$ or 1.

32. A device as claimed in any one of Claims 28 to 31, in which the liquid crystal layer is an out-of-plane switching nematic liquid crystal.

33. A reflective liquid crystal device comprising a linear polariser, a polarisation preserving reflector, and a retarder arrangement comprising a first retarder disposed between the polariser and the reflector and a second retarder disposed between the first retarder and the reflector, at least one of the first and second retarders comprising a twisted retarder, and at least one of the first and second retarders comprising a liquid crystal layer which is switchable between a non-reflective device state, in which the retardation of the retarder arrangement is equal to $(2n+1)\lambda/4$ where n is an integer and λ is a wavelength of visible light, and a reflective device state.

34. A device as claimed in any one of Claims 1 and 12 to 33, in which $n=0$.

35. A device as claimed in any one of the preceding claims, in which λ is between substantially 500 and substantially 570 nanometres.

36. A device as claimed in Claim 35, in which λ is between substantially 510 and substantially 550 nanometres.

37. A device as claimed in Claim 36, in which λ is between substantially 525 and substantially 530 nanometres.

38. A device as claimed in any one of the preceding claims, in which the retarder arrangement has a retardation substantially equal to $m\lambda/2$ in the reflective device state, where m is an integer.

39. A device as claimed in any one of the preceding claims, in which the reflector comprises a plurality of discrete picture element electrodes.

40. A device as claimed in any one of Claims 1 to 18, in which at least one of the first, second and third retarders is a twisted retarder.

The Patent Office

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Application No: GB 9622733.5
Claims searched: 1 to 40

Examiner: Mr.G.M Pitchman
Date of search: 8 January 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G2F (FSX)

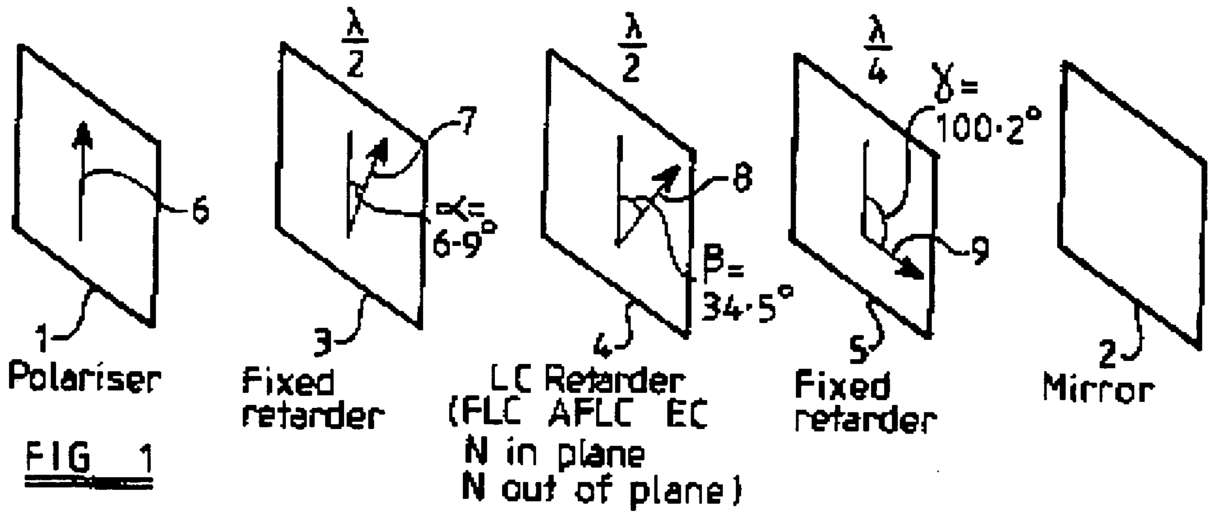
Int Cl (Ed.6): G02F 1/1335

Other: ONLINE: EDOC WPI JAPIO INSPEC

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	EP 0699938 A2 (SHARP)-see abstract	1-40
A	EP 0679921 A1 (OIS)-see abstract	1-40
A	EP 0298602 A1 (MITSUBISHI)-see abstract	1-40

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		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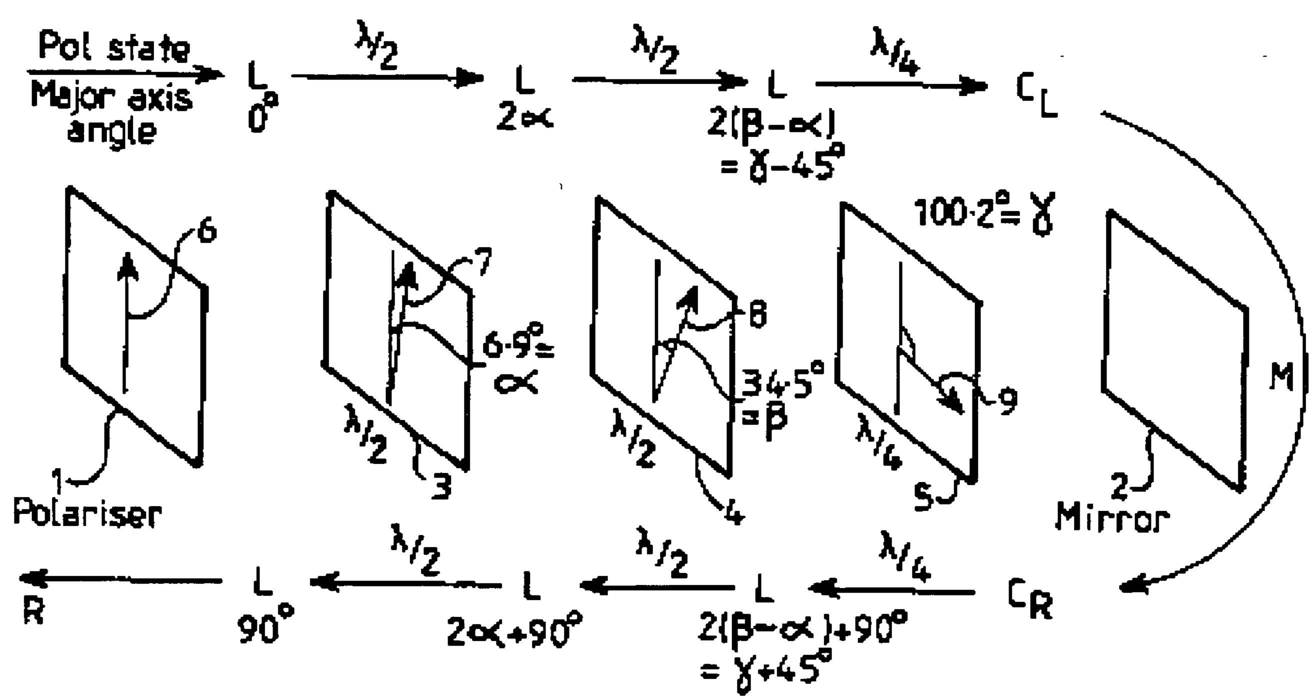
λ/2
λ/4
γ= 100·2°
7
6
α= 6·9°
8
β= 34·5°
9
1
Polariser
3
Fixed retarder
4
LC Retarder (FLC AFLC EC N in plane N out of plane)
5
Fixed retarder
2
Mirror

FIG 1

FIG 2


Pol state
Major axis angle
L 0°
λ/2
L 2α
λ/2
L 2(β−α) = γ−45°
λ/4
C_L
100·2°= γ
6
7
6·9°= α
8
34·5° =β
9
λ/2
λ/2
λ/4
1
Polariser
3
4
5
2
Mirror
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λ/2
L 2α+90°
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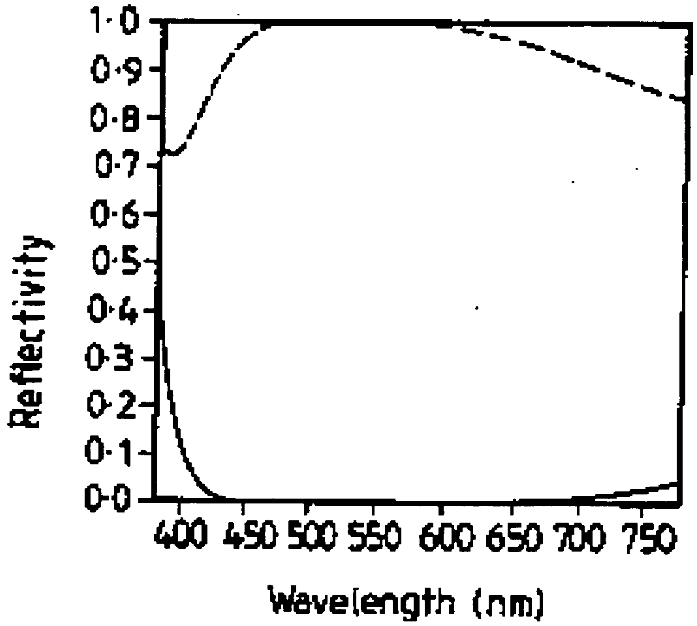
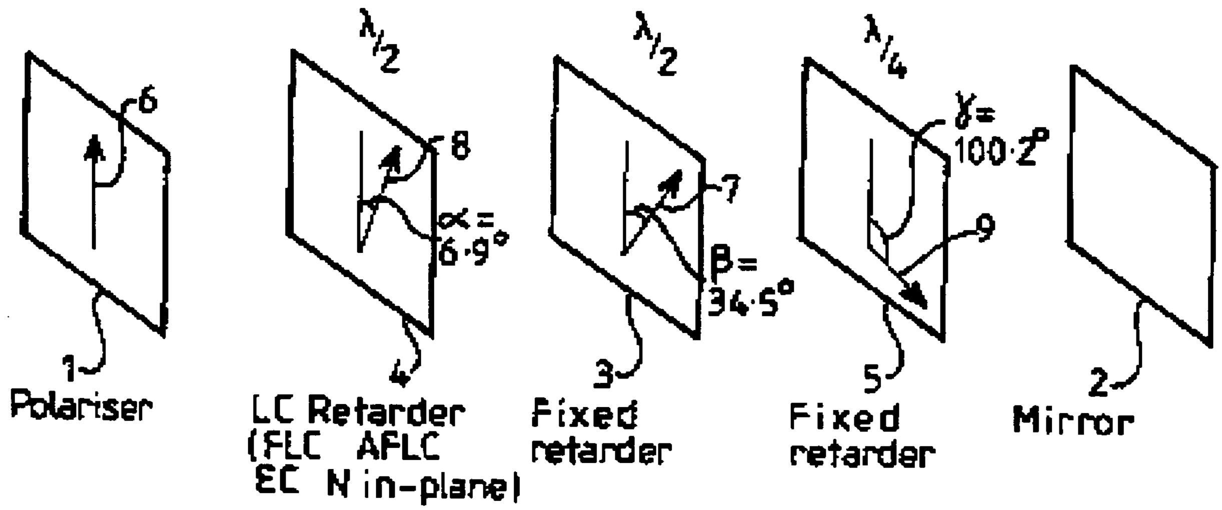
λ/4
C_R



1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·0
Reflectivity
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 3



λ/2
λ/2
λ/4
6
8
7
9
α = 6·9°
β = 34·5°
γ = 100·2°
1
Polariser
4
LC Retarder (FLC AFLC EC N in-plane)
3
Fixed retarder
5
Fixed retarder
2
Mirror

FIG 4

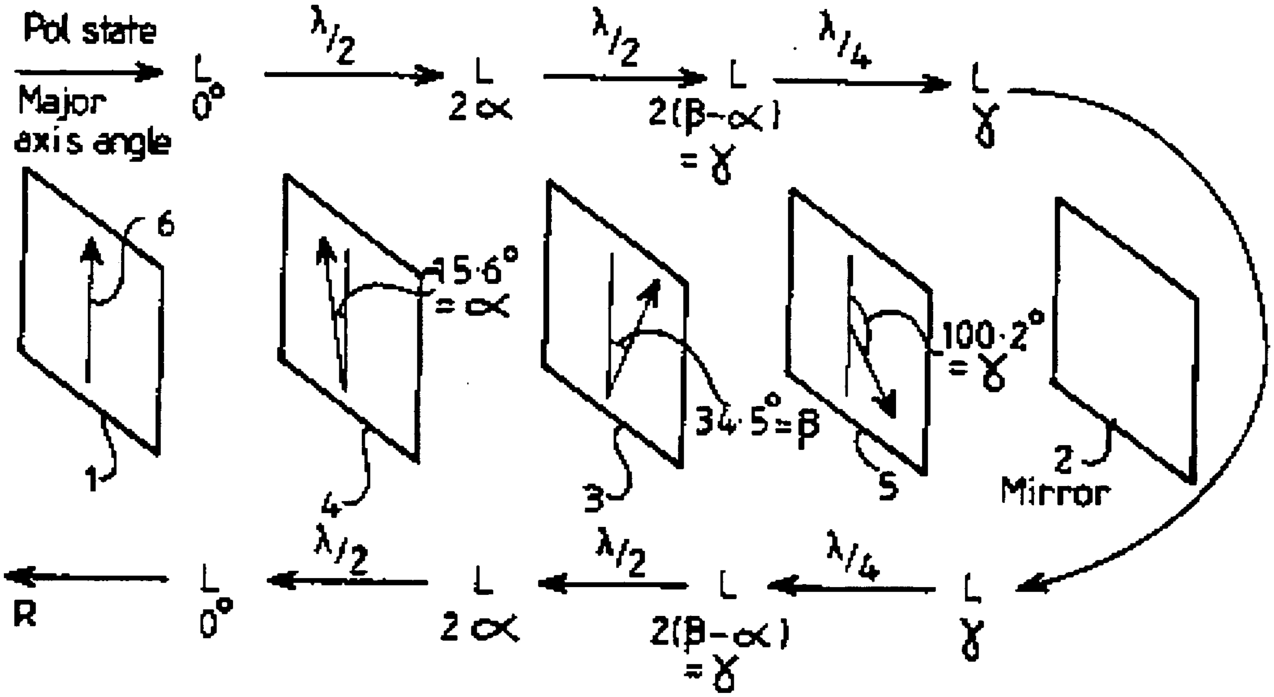

Pol state
Major axis angle
L 0°
$\lambda/2$
L 2α
$\lambda/2$
L $2(\beta-\alpha) = \gamma$
$\lambda/4$
L γ
6
15·6° = α
34·5° = β
100·2° = γ
1
4
3
5
2
Mirror
R
L 0°
$\lambda/2$
L 2α
$\lambda/2$
L $2(\beta-\alpha) = \gamma$
$\lambda/4$
L γ

FIG 5

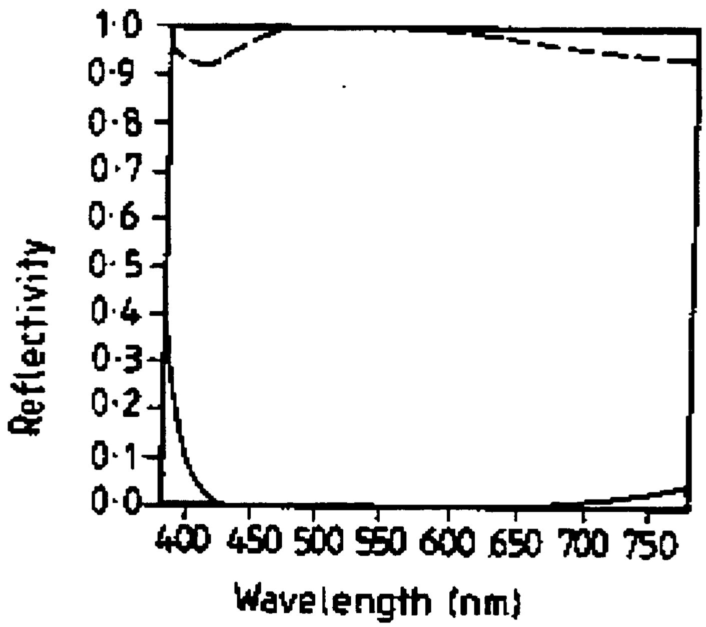

1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·0
Reflectivity
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 6

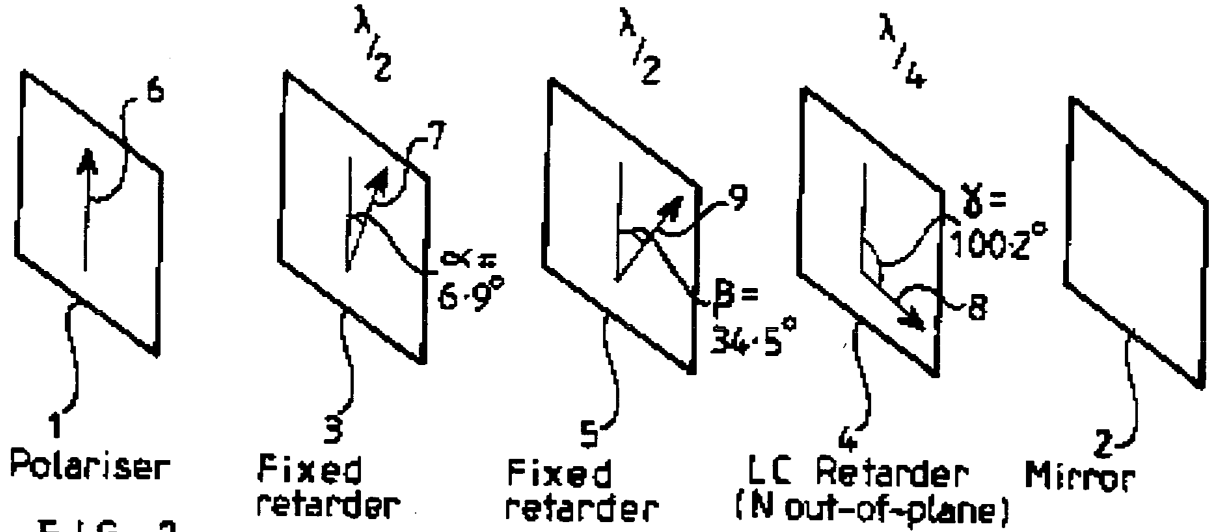

λ/2
λ/2
λ/4
6
7
9
α = 6·9°
β = 34·5°
γ = 100·2°
8
1
Polariser
3
Fixed retarder
5
Fixed retarder
4
LC Retarder (N out-of-plane)
2
Mirror

FIG 7

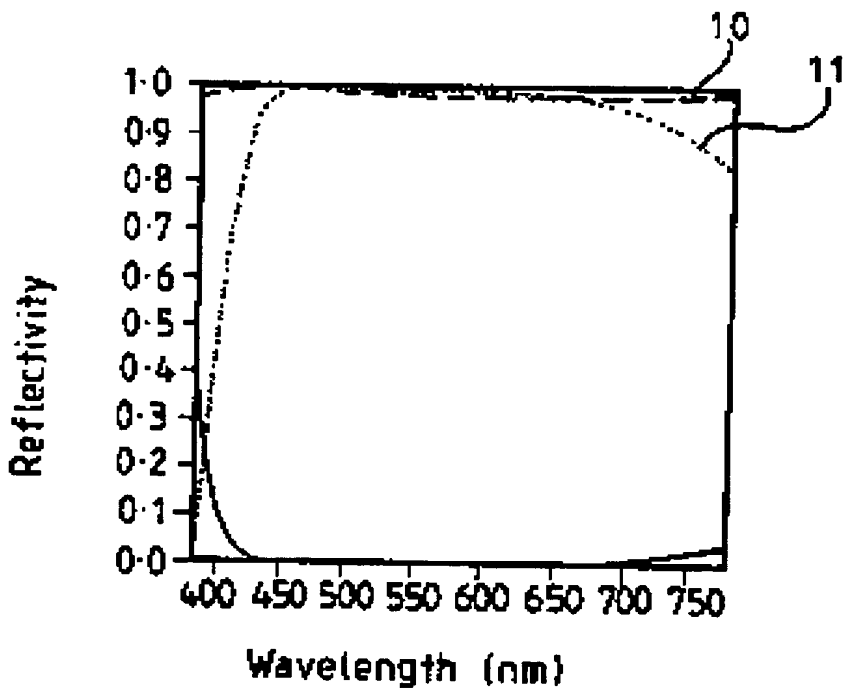

10
11
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·0
Reflectivity
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 8

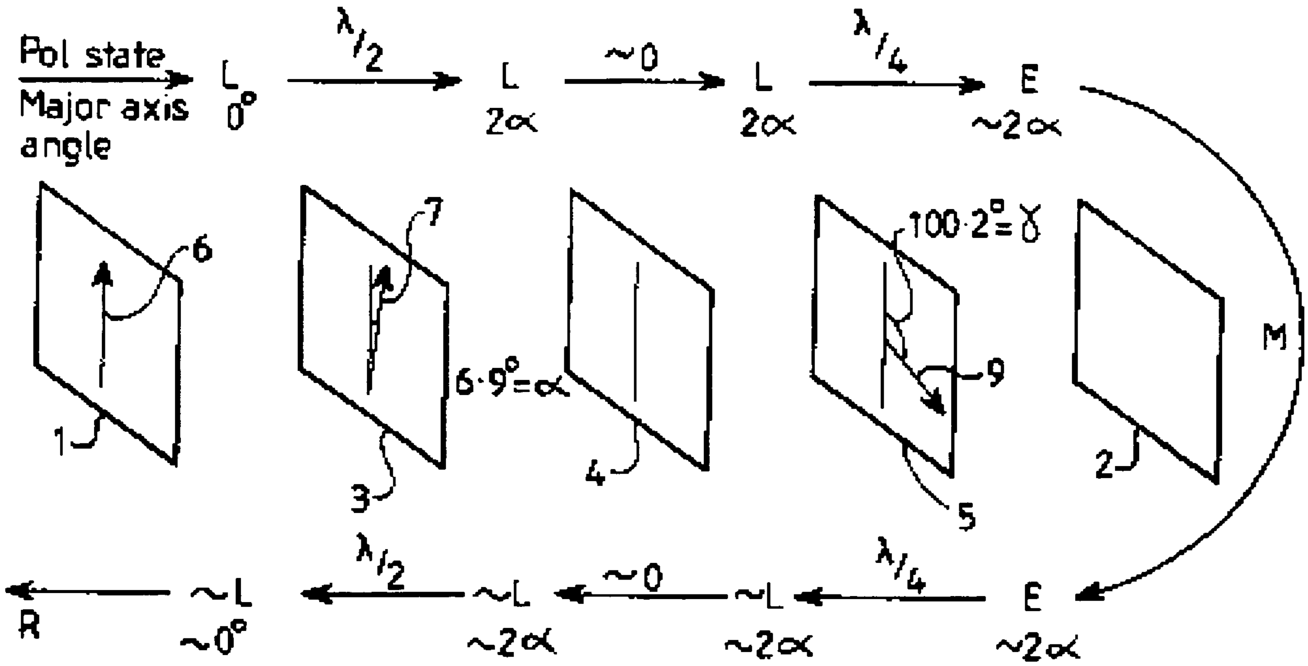

Pol state
Major axis angle
L
0°
$\lambda/2$
L
2∝
~0
L
2∝
$\lambda/4$
E
~2∝
6
7
100·2°=γ
6·9°=∝
9
M
1
3
4
5
2
R
~L
~0°
$\lambda/2$
~L
~2∝
~0
~L
~2∝
$\lambda/4$
E
~2∝

FIG 9

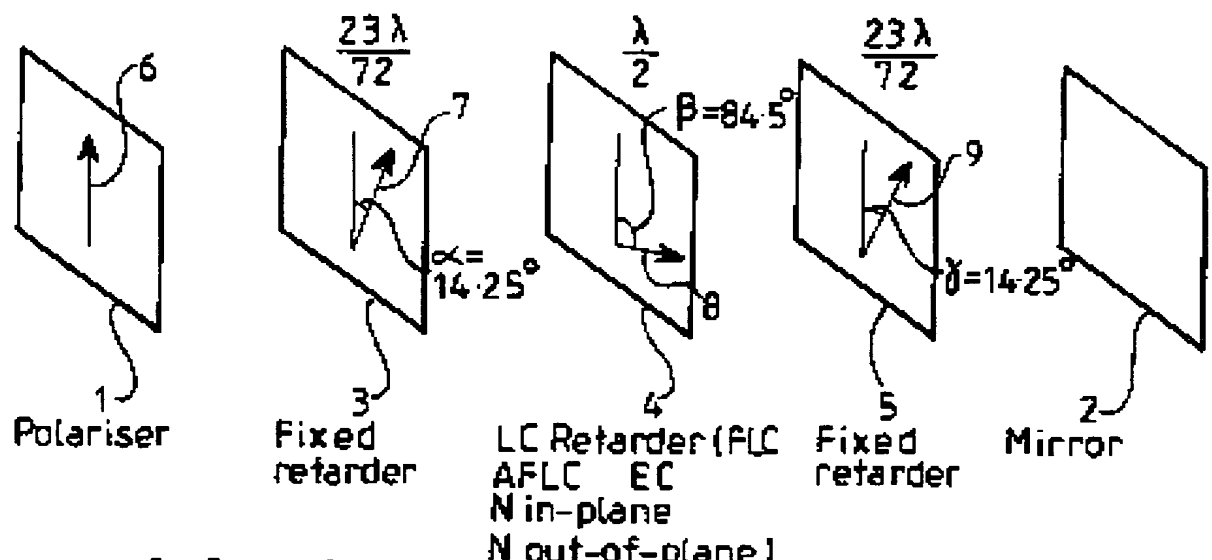

$\frac{23\lambda}{72}$
$\frac{\lambda}{2}$
$\frac{23\lambda}{72}$
6
7
β=84·5°
9
∝=
14·25°
8
γ=14·25°
1
Polariser
3
Fixed retarder
4
LC Retarder (FLC
AFLC EC
N in-plane
N out-of-plane)
5
Fixed retarder
2
Mirror

FIG 10

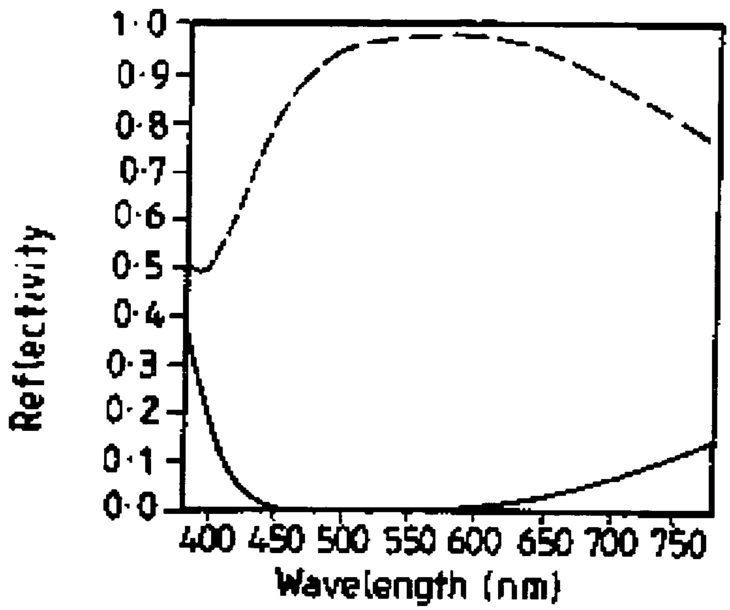
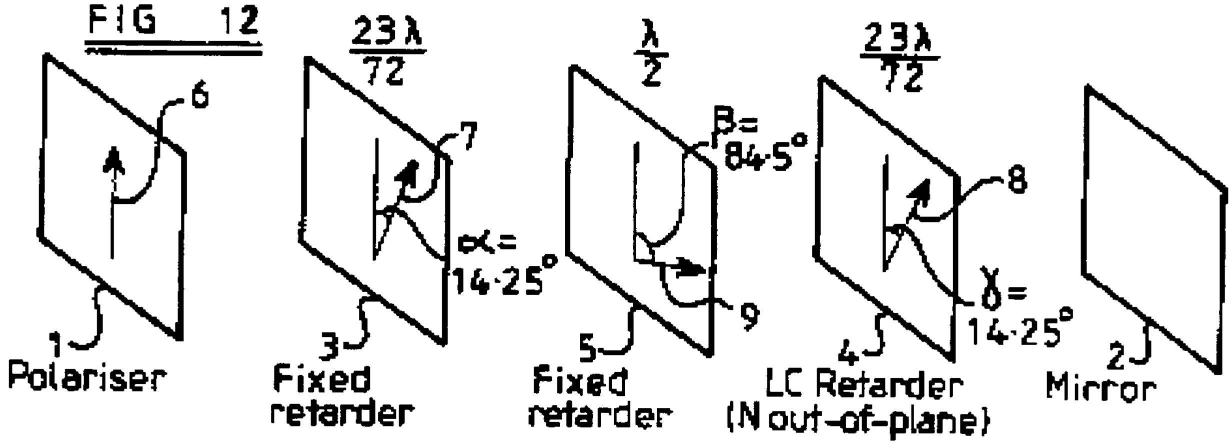


FIG 11

FIG 12



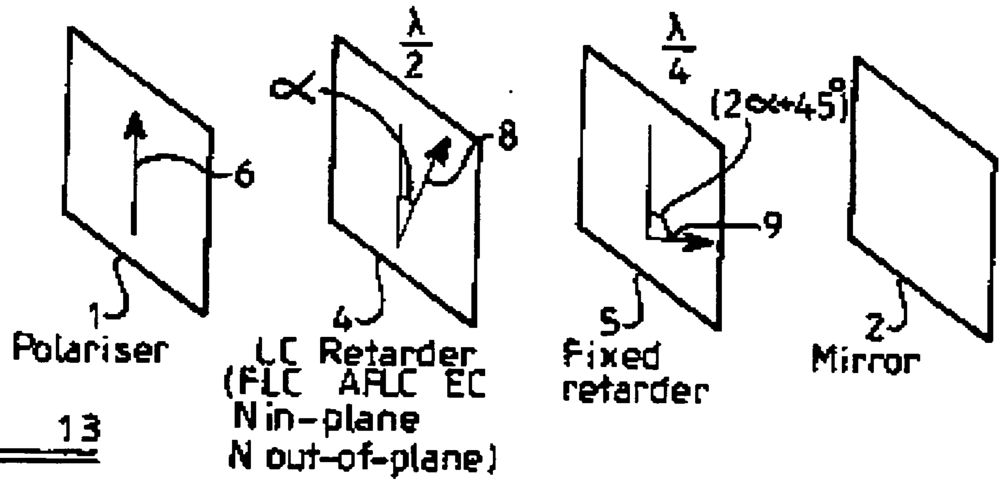


FIG 13

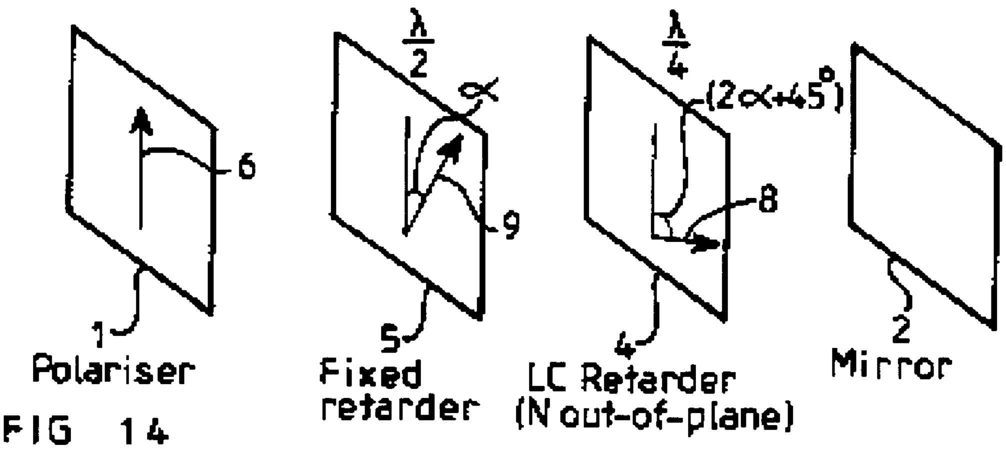


FIG 14

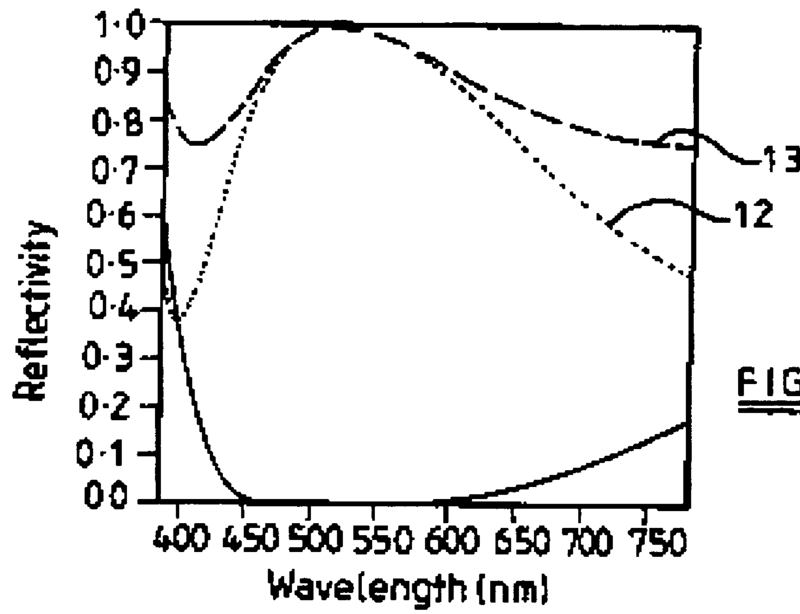


FIG 15

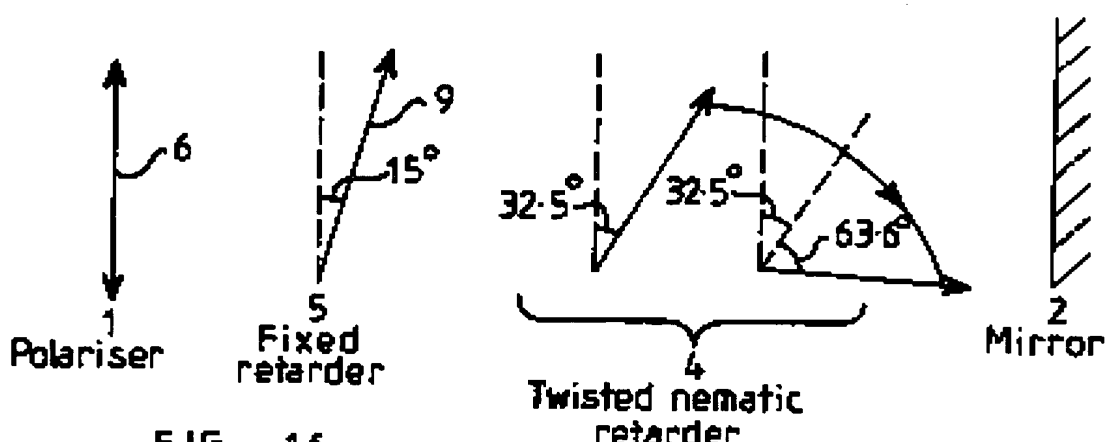


FIG 16

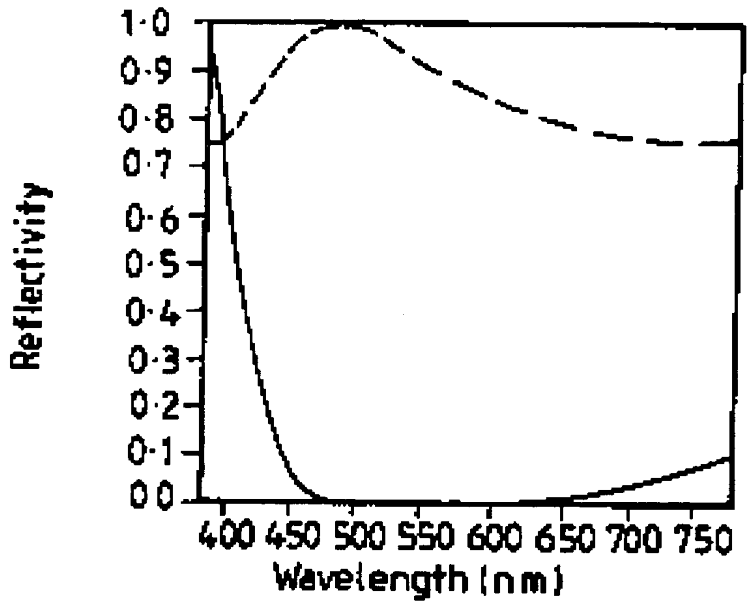

1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0 0
Reflectivity
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 17

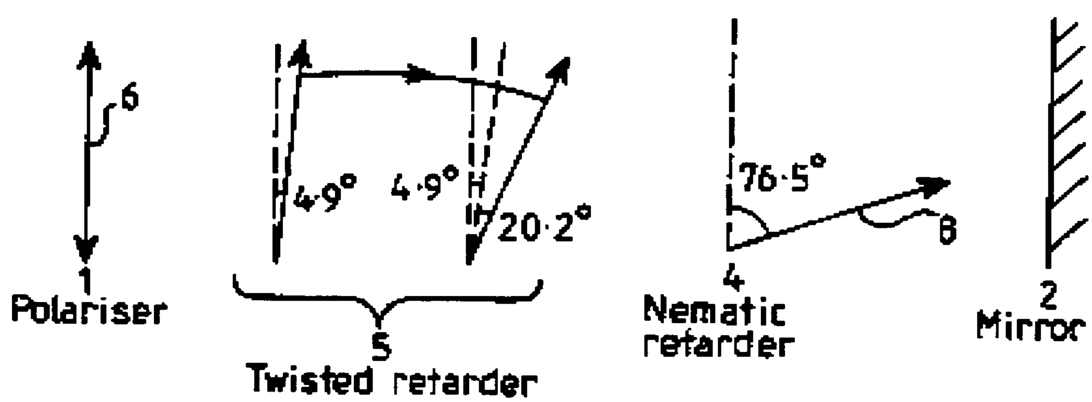

6
4·9°
4·9°
20·2°
76·5°
8
1
Polariser
5
Twisted retarder
4
Nematic retarder
2
Mirror

FIG 18

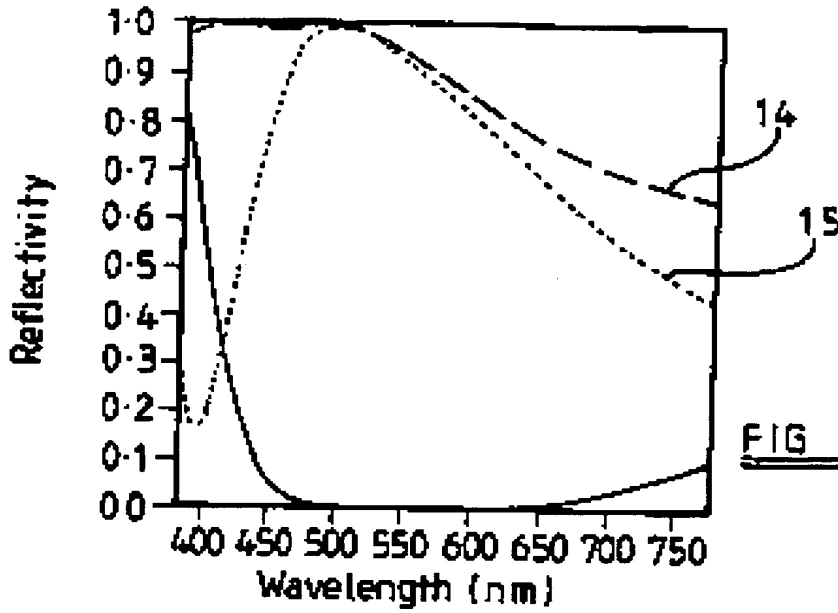

1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·0
Reflectivity
400 450 500 550 600 650 700 750
Wavelength (nm)
14
15

FIG 19

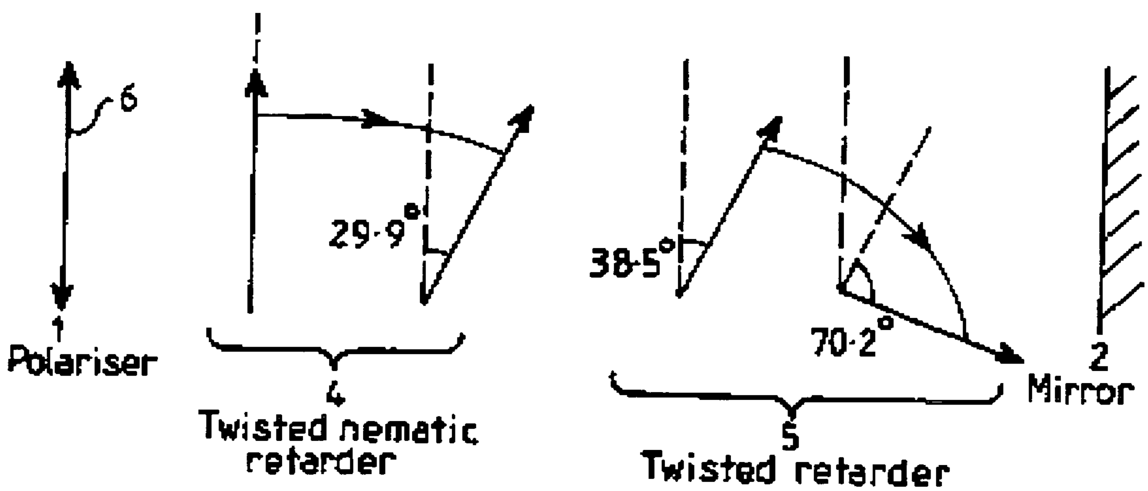

6
29·9°
38·5°
70·2°
1
Polariser
4
Twisted nematic retarder
5
Twisted retarder
2
Mirror

FIG 20

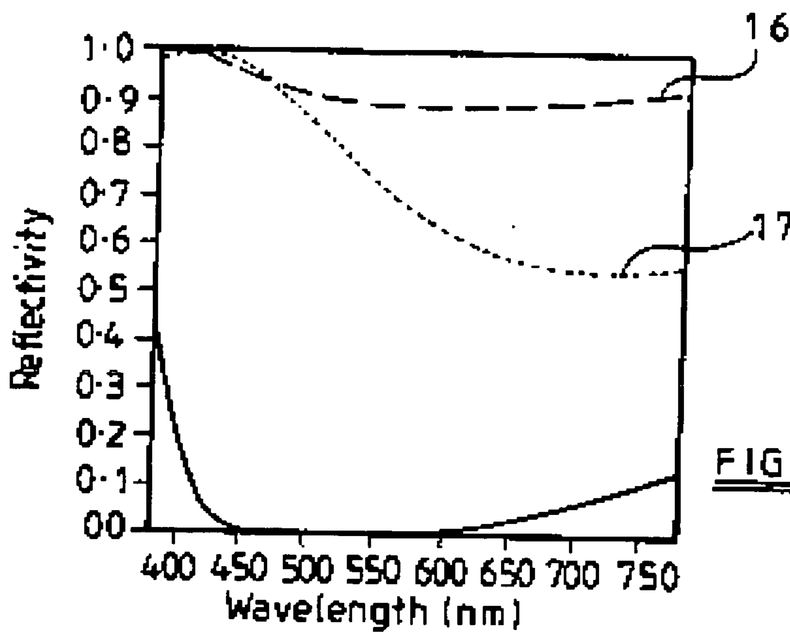
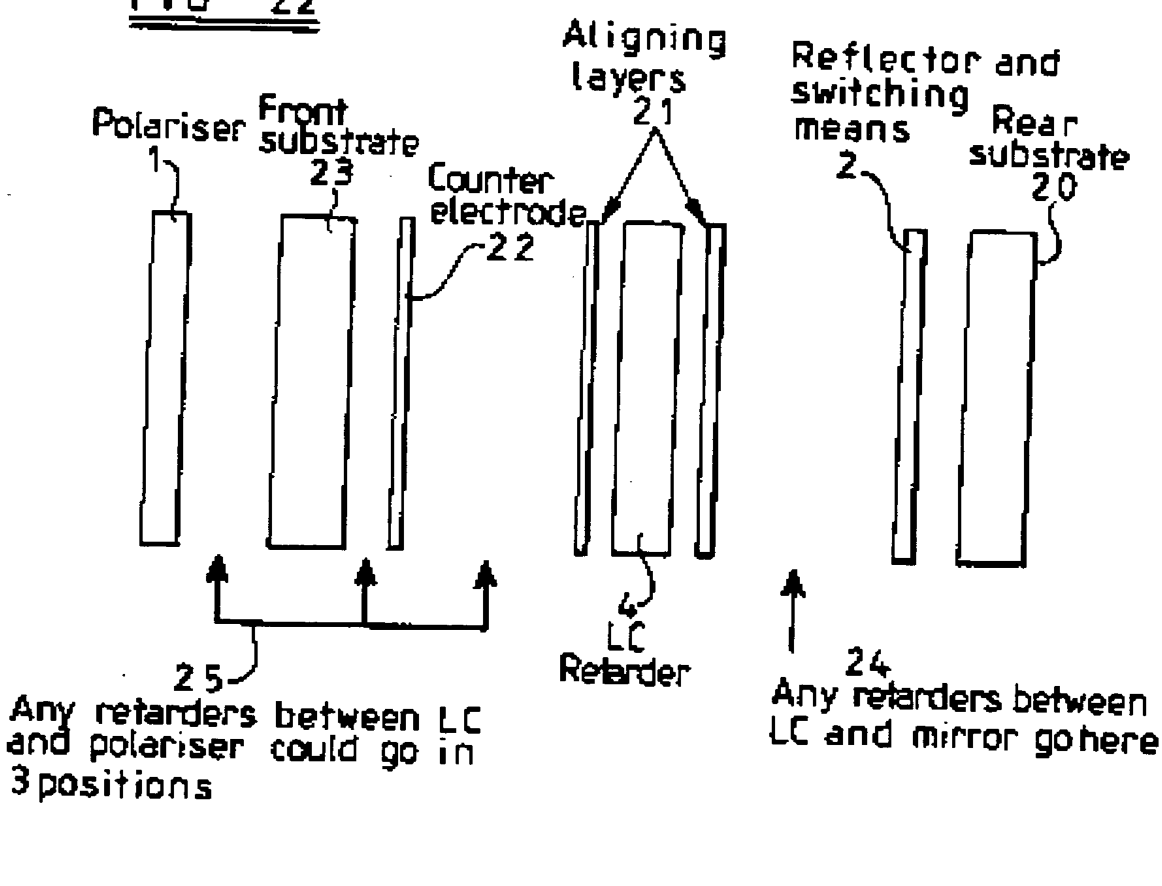

16
17
Reflectivity
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
00
400 450 500 550 600 650 700 750
Wavelength (nm)

FIG 21

FIG 22


Polariser
1
Front substrate
23
Counter electrode
22
Aligning layers
21
Reflector and switching means
2
Rear substrate
20
4
LC Retarder
25
Any retarders between LC and polariser could go in 3 positions
24
Any retarders between LC and mirror go here